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ACTMO
An Agricultural Chemical Transport Model

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CONTENTS

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An Agricultural Chemical Transport Model

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SUMMARY

The use of chemicals is an important feature of modern agriculture, but the movement of the chemical from its point of application constitutes a potential hazard. The evaluation of this hazard is very difficult because the agricultural watershed contains many complex processes that dynamically respond to weather elements. To aid in evaluating this hazard, a mathematical model has been developed and a computer program written that describes the movement of chemicals in and across an agricultural watershed. For each storm in series the objective is to use the model to predict the concentration of a chemical in the runoff water, the total amount carried by the runoff water and sediment, and the location and concentration of the chemical remaining on the watershed. This report describes the rationale used to develop the model as well as a couple of tests of the model that illustrate and evaluate its use.

INTRODUCTION

Maintaining a high quality of water resources, conserving land resources, and increasing agricultural efficiency are vital ingredients to national sustenance. The movement of chemicals and soil from agricultural areas can endanger these ingredients.

The Federal Water Pollution Control Act Amendments of 1972 stress several requirements concerning agriculture. These include guidelines for identifying and evaluating the nature and extent of pollution from agriculture lands, and the processes, procedures, and methods for controlling it. The Administrator of EPA, in cooperation with the Secretary of Agriculture and other agencies, is charged with developing the necessary research to provide the needed information.

Ignorance of essential factors in a complex system such as agricultural watersheds can lead to excessive or inadequate controls. The result can be economic or environmental damage requiring years to correct. The factors in a watershed system are interrelated, dynamic, and influenced by uncontrollable weather elements. Optimum management of an agricultural area requires predictions of the behavior of the watershed to changes in farm management practices. Quantification of the potential for any amount of chemical applied to any part of a watershed moving to the streams and ground water requires a comprehensive sequential accounting in time and space for the entire watershed.

One of the better means for obtaining reasonable predictions of complex systems is to perform the accounting in terms of a mathematical model. The operation of the computational model on modern computers permits evaluation of numerous agricultural management alternatives and various climatic sequences. In addition, testing and development of a model serves as a research tool to integrate multidisciplinary projects and to reveal gaps in information and understanding.

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The essentials for computing movement of chemicals applied to agriculture require a distributed system of watershed hydrology, erosion, sedimentation, and chemical behavior. To establish a continuum for discussion and improvement, the USDAHL-74 Model was used for watershed hydrology, the Universal Soil Loss Equation (USLE) was adapted to compute the erosion, and sedimentation on physiographic areas in the watershed. A method was developed to compute the interactions of agricultural chemicals with the soil-water-plant system in the physiographic areas.

OBJECTIVES

The objectives for this model are to predict the concentration and amount of the chemical in the runoff water and on the sediment at the watershed outlet, and to predict the location and concentration of chemicals that are leached and moved spatially through the soil of the watershed. The model includes such management options as the time, the rate, and the type of chemical applied, changes in crop pattern, and tillage practices. To facilitate application, topographic, soil, and land-use maps of the watershed are used to estimate model parameters. Ultimately, we hope, all watershed information can be obtained from SCS farm plans. We assume that published data from the field and laboratory can be used for estimating the chemical interaction with the soils and water.

Considerable research will be required to achieve the objectives. This general framework constituting initial efforts divides the model into three submodels: A chemical, an erosional, and a hydrological submodel. The erosion submodel receives data from the hydrology submodel while the chemical submodel receives data from both the hydrological and erosional submodels. This separation facilitates the interchange of other chemical, erosional or hydrological submodels and modifications. Objectives of the initial effort were to achieve an operating version of ACTMO for certain limited conditions. The model must then be tested, modified, verified, and extended to major agricultural areas before it can be considered a finished product.

INITIAL MODEL BOUNDARIES

The watershed is limited to an area that can be represented by a single rainfall input (a single gage or a composite of several gages). A farm-size area is convenient because it reflects actual management decisions. For example, a row crop requiring a large amount or number of chemicals can be moved to various parts of the watershed. If the scope of consideration is larger than a single field, the dilution of the chemical by water and sediment from nontreated areas is a major consideration. The Corn Belt area was used in the initial development because it is one of the major areas of heavy fertilizer and pesticide use. The initial version was not designed to be applicable to the important agricultural watersheds located in flat coastal or delta regions or containing irrigated or forested land.

The transport scale is divided into two phases. The first is chemical application, degradation, redistribution by cultivation, and nitrate mineralization and uptake by the plants. The second phase is the transportation of chemicals by water and sediment movement.

The operation of the model through the first phase following application of a nonpersistent chemical is adequate to describe the potential acute toxicity problem. Its operation through numerous phases describes the behavior of persistent chemicals that can accumulate and pose chronic toxicity or eutrophication problems.

The initial version is limited to tracing a single application of one chemical at a time. The application of more than one chemical can be handled by repeating the chemical submodel for each chemical. This assumes no interaction between chemicals, which is usually the case, and no direct effect by the chemicals on the erosion or hydrologic behavior of the watershed. Fertilizers and herbicides do affect crop cover and in turn, the hydrologic and erosion response. This interaction is not considered in the initial version. Repeated application of the same chemical is important, but programming difficulties must be resolved. Salt movement and salinity are additional problems not included in this version. In fact, the characteristics of these problems are sufficiently different that an entirely new chemical section may be required.

The erosion submodel is limited to rill and interrill components of sheet erosion. However, the different characteristics of rill armoring and preformed rills are not considered. Local deposition is predicted throughout

a watershed, but differences in erodibility and texture of the deposited material are not considered for subsequent storms. Sediment from areas such as gullies, roads, and construction sites is not accounted for, although such sediment may be significant in downstream chemical transport. The interactions of fertilizers, soil conditioners, and other cultural activities with the soil properties known to affect erosion are not considered, nor is the time rate-of-change of properties considered.

The hydrology submodel computes average values for evapotranspiration, infiltration, and runoff for each zone in the watershed. Therefore, chemical considerations limit a single crop for each zone because average values for dissimilar crops will not provide adequate information for chemical movement. Only two layers per zone are physically defined and provide useable data. Two other layers are empirically defined as storage from recession flows. The subsurface movement of water laterally from each zone is routed across the alluvium or directly into the channel. Snowmelt is computed in the model for all precipitation increments identified as snow in the input data.

THE GENERAL FRAMEWORK

As previously pointed out, ACTMO is divided into three sections to provide a means where alternate chemical, erosional, or hydrological submodels could be easily substituted. Figure 1 summarizes the general framework of the model in a flow diagram while table 1 describes the information transmitted in the input and output files of ACTMO.

The USDA Hydrograph Lab model was adopted as the hydrologic submodel because it was operational, was calculating most of the variables considered necessary for a transport model, and utilized parameters readily available from soil survey data. The hydrology submodel was developed from data on a variety of watersheds across the country and, therefore, is potentially broad based. The erosional and chemical submodels were developed specifically for this model, combining many previously published concepts.

The processes involved in chemical transport indicate the following factors are important. The soil moisture and temperature influence the breakdown of many chemicals and the mineralization of nitrogen, but nitrogen uptake is expected to be correlated with transpiration. The leaching efficiency of water tends to be lower as gravitational water percolates through the soil. The amount of runoff is obviously an important variable as is the relative amount of lateral flow for mobile chemicals. Therefore, the hydrology submodel supplies the chemical submodel the following variables: The temperature, and for each layer in a zone the evapotranspiration and

Table 1.—Description of the information transmitted in the input-output files of ACTMO

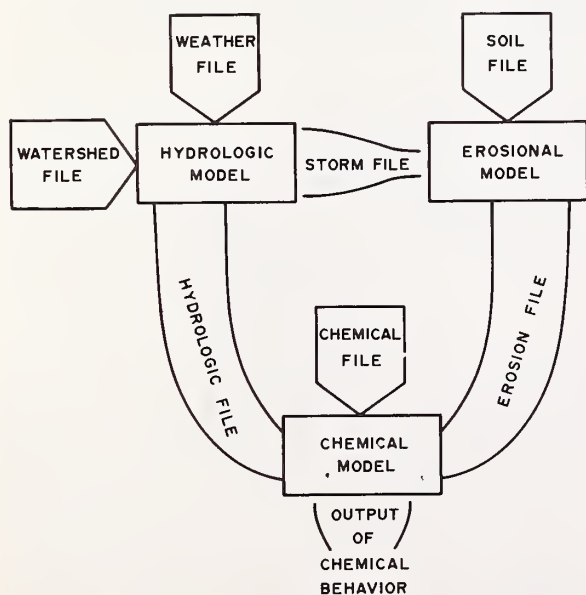| File	Information
Weather ...	Rainfall, temperature, pan evaporation.
Watershed ··	Zone sizes and cascading, soil hydrologic properties, crop pattern and characteristics, tillage operations.
Storm ····	Length, slope, and cascading of zones, runoff, infiltration, and rainfall intensity.
Soil	Soil texture.
Erosion....	Compartment areas, enrichment coefficient, soil texture, infiltration, runoff, erosion, and deposition.
Hydrological	Cultivations, soil properties, time-averaged temperature, soil moisture, and ET, lateral and vertical flow, soil water when the storm starts.
Chemical ..	Date, amount, and type of chemical application; treated area; soil chemical interactions; and critical levels.
Output of Chemical Behavior...	Chemical lost in runoff and erosion. Concentrations in runoff. Chemical left in each compartment. Location and concentration of peak in each compartment.

Figure 1.—Flow diagram for the input-output files in ACTMO.

soil moisture averages between storms, the infiltration before runoff starts, infiltration during runoff, volume of runoff, the lateral and vertical flow rates for each zone, and the soil moisture in each layer of each zone at the start of the storm.

Chemicals adsorbed to the soil are subject to erosion as a transport mechanism. The chemical concentration in the soil varies with depth because of the application method and the amount of leaching. Therefore, both rill and interrill or surface erosion are calculated. Finally, a decrease in the transport capacity of the runoff can cause deposition of the sediment. Chemicals are usually preferentially adsorbed by the finer sediment fractions which are the last to be deposited and, therefore, the

composition of the sediment which is enriched with the fine material is calculated. In summary, the erosion submodel supplies the chemical submodel with estimates of interrill erosion, rill erosion, area and depth of rills, amount of deposition, and the enrichment of the eroded sediment relative to the clay fractions of the original soil.

The Universal Soil Loss Equation was modified to compute the erosion and deposition information for the chemical submodel. The rainfall factor in this equation was adjusted from an annual average to a storm basis by the rainfall intensity, the amount of runoff, and the peak rate of runoff variables supplied by the hydrology submodel.

THE WATERSHED TRANSFORMATION

On a multicropped watershed one must anticipate that only part of the watershed might be treated with a chemical. Some means must be used to transform the watershed defined by physical characteristics, such as crop fields, into computational units. A zone, the computational unit for the hydrology submodel, is constructed by grouping fields of the same crop, or

major soil areas, or land-capability classes or whatever physical feature is recognized as important. The zones typify the elevation sequence of uplands, hillsides, and bottomlands. The percent of each zone contributing surface runoff to lower zones is estimated by observations from the soils and topographic maps. The average downslope dimensions of each zone is the length of
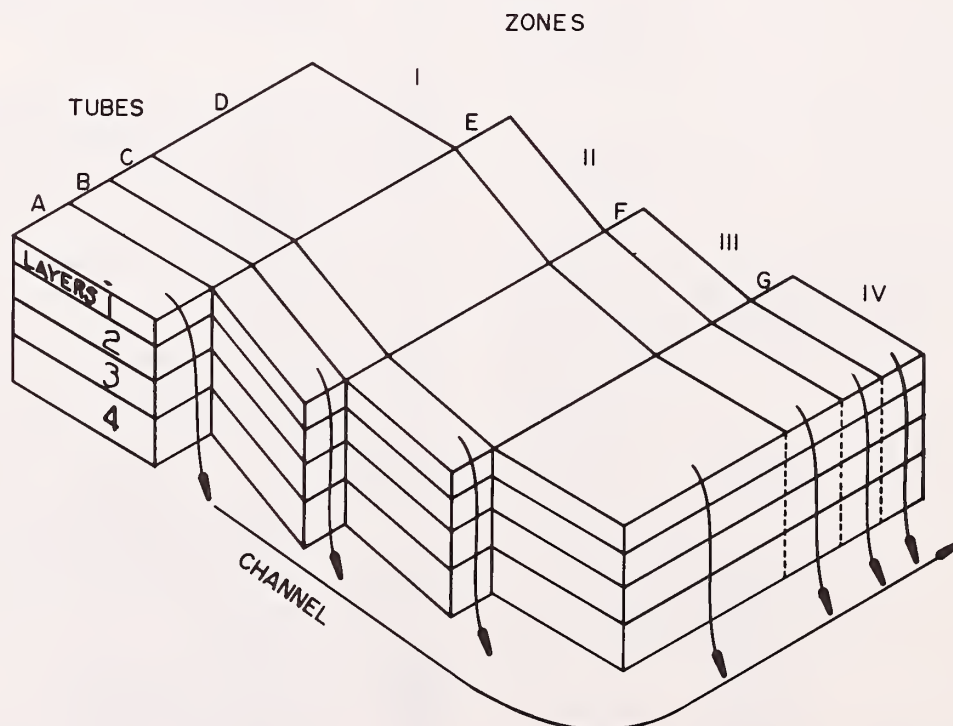

Figure 2.—A three-dimensional transform of the watershed into computational units.

overland flow in the zone. The results are illustrated in figure 2 where four zones with different slopes are each divided into four compartments creating seven tubes.

Each tube is the area between adjacent streamlines from flow net theory. The flow of water and sediment is assumed to occur along the line of steepest descent, representing flow over an isotropic surface. This provides a situation analogous to the natural sequence of flow while maintaining the distributed effect. The size of the incremental areas within a zone or compartment is calculated from the average zone length and the fraction of the zone area that contributes directly to the channel. Each compartment is intended to be a homogeneous unit for computing infiltration, evapotranspiration, overland flow, and net erosion or deposition. Soil and water

lost from one compartment are considered to be additions to the top of the adjacent downslope compartment where similar calculations are made. This process is continued down to the watershed main channel.

Figure 2 also illustrates the vertical dimension that is considered. The hydrology submodel treats the first layer as the "A" horizon or plow layer and the second layer as the remainder of the potential root zone. The other two layers are defined empirically as storage from recession outflows. The chemical submodel uses the same layers to compute the chemical interactions with the soil. Although coefficients of adsorption, dispersion, and breakdown could be handled as continuous functions of depth, the degree of refinement is limited by the degree of hydrological definition of the soil.

SUBMODEL DESCRIPTION

This section provides a detailed description of each submodel. Such a description is not essential for an overview, but a model, like a chain, is no better than its weakest link. In this section all of the relations and assumptions are laid bare for examination.

The description of each submodel is essentially an independent paper. The section on the hydrology submodel is a recent revision of "USDAHL-70 Model of Watershed Hydrology" (20).[4] The erosion-deposition submodel was developed by C. A. Onstad while M. H. Frere developed the chemical and nitrate submodels.

The Hydrology Submodel for ACTMO

The USDAHL-74 Revised Model of Watershed Hydrology[5]

Hydrologic Grouping of Soils and Land Use

Soils on each watershed are grouped by land capability classes, as illustrated in figure 3, to form hydrologic response zones for computing infiltration, evapotranspiration, and overland flow. Zones indicated for each watershed typify the elevation sequence of uplands, hillsides, and bottom lands in these areas. Zones are always numbered in a downslope order because computations assume that some of the runoff will cascade over successive zones. For example, on the Coshocton watershed an estimated 60 percent of Zone 1 runoff flows directly onto the alluviums of Zone 3, and only 40 percent cascades to soils of Zone 2.

The watershed description data published by the Agricultural Research Service field stations (48) give percentages of area of major soils and of land-capability classes. Moisture-tension data (table 2) published by the USDA Hydrograph Laboratory (22) or the Soil Survey Investigations Reports of the Soil Conservation Service[6] provide soil profile descriptions for computing weighted averages of hydrologic capacities (8) of soils in each zone. Specific gravity was estimated at 2.65 for all soils in computing total porosities. Moisture at 0.3 bar tension was used for field capacity in dividing total retention capacities (S) into moisture freely drained by gravity (G) and moisture drained by vegetation (AWC). The lower limit of AWC is assumed to be the moisture at 15 bars tension. Table 3, by C. B. England, is a summary of a great many samples giving S, G, and AWC in percent volume of textural horizons. Percentages are applied to depths of "A" horizons or to plow depths in nonlayered soils, and to depths of maximum root penetration as might be limited by hardpans, gravelly layers, or other textures unsuited for root growth. The input format of the model accepts G and AWC in percentages by volume and applies them to soil depths to compute volumes.

Evapotranspiration

Evapotranspiration potentials are estimated by coefficients applied to published pan-evaporation data. The method is a combination of techniques developed by Mustonen and McGuiness (32), Jensen (25), and Pruitt (38) adapted for use with cardinal temperatures presented in table 4 in estimating plant growth. Figure 4 is a plotting of XGI, cardinal temperature functions

Table 2.—Profile description and physical properties—Cecil Gritty Sandy Loam

Location: Blacksburg, Virginia; Brunswick County, Rocky Run Branch Watershed, located in pasture 75′ SW of
          fence, 400 yds. W of county road #656.
Vegetation and land use: Pasture.
Topography: Gently sloping.
Drainage: Well-drained.
Parent material: Granite gneiss and schist.
Described and sampled by: K. Fussell, J. Williams, and J. B. Burford.

Horizon	Description	Available moisture	
		Per inch of soil	In horizon
		Inches	*Inches*
Ap	0 to 6 inches. Dark yellowish brown (10YR 4/4) gritty sandy loam; very friable; weak medium granular structure; many fine roots; medium acid; few small peds of red (2.5YR 4/6) brought up from lower horizons by plowing; abrupt wavy boundary.	0.10	0.60
B22t.	6 to 15 inches. Red (2.5YR 4/6) clay with few fine mottles of yellowish red (5YR 5/8); some ped faces are coated with yellowish red (5YR 4/8) clay, which is apparently result of root and worm action; firm; moderate medium subangular blocky structure; thin continuous clay films; few mica flakes; common fine roots; occasional quartz rock less than 1/2″ in diameter; medium acid; clear wavy boundary.	.07	.63
B23t.	15 to 31 inches. Red (2.5YR 4/6) clay loam with common fine faint mottles of yellowish red (5YR 5/8) and common fine distinct mottles of yellowish brown (10YR 5/8); moderate medium and fine subangular blocky structure; friable; thin clay film on most ped faces; common mica flakes; 10 percent grit by volume; few fine roots; strongly acid; clear wavy boundary.	.06	.96
B31	31 to 42 inches. Red (2.5YR 4/6) clay loam with many medium faint mottles of yellowish red (5YR 5/8) and few medium distinct mottles of strong brown (7.5YR 5/8) and reddish yellow (7.5YR 6/8); friable; moderate to weak medium and fine blocky and subangular blocky structure; patchy clay film; many mica flakes; 10 percent grit by volume; strongly acid; clear smooth boundary.	.13	1.43
B32	42 to 56 inches. Mottled colors of red (2.5YR 4/8), yellow red (5YR 5/8), reddish yellow (7.5YR 6/8), very pale brown (10YR 7/4) highly weathered granite gneiss and schist with few pockets of light clay loam; friable; weak fine and medium subangular blocky structure; many mica flakes; slimy and greasy to the feel; 10 percent grit by volume; few patchy clay films; very strongly acid; gradual wavy boundary.	.18	2.52
C	56 to 71 inches plus. Mottled colors of yellowish red (5YR 5/8), red (2.5YR 4/6), reddish yellow (5YR 6/8), and very pale brown (10YR 7/4) highly weathered granite gneiss and schist; silt loam with 10 percent grit by volume.	.18	- - - -

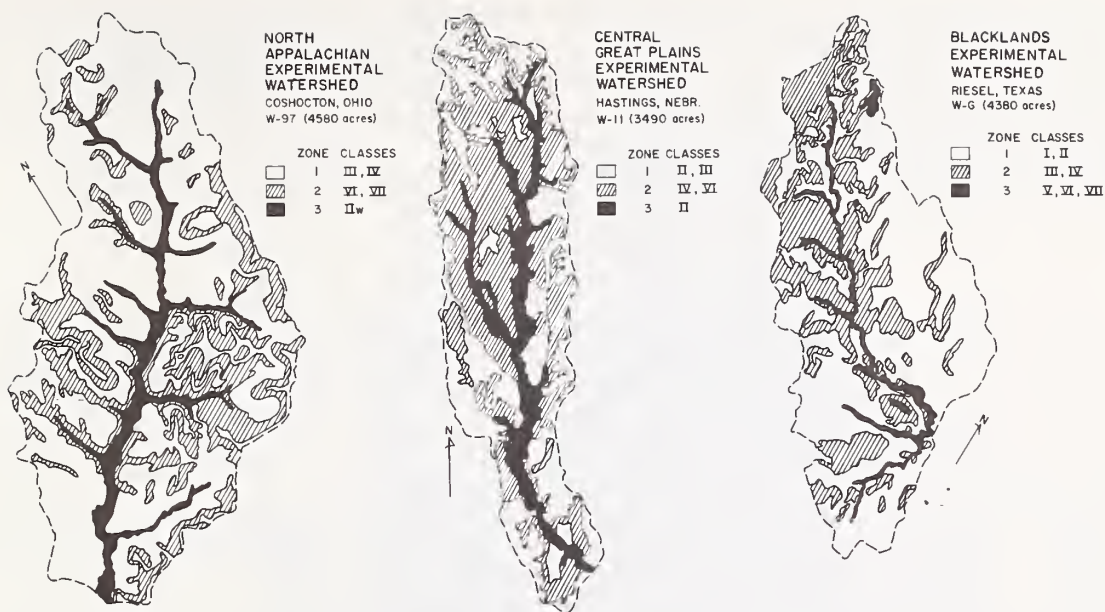| Horizon	Depth	Bulk density	Moisture as percent of dry weight at respective atmospheres of tension				
			0.1	0.3	0.6	3	15
	Inches	*G./cc.*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Ap	0 - 6	1.72	15.24	12.35	10.30	9.21	6.34
B22t.	6 - 15	1.33	26.90	23.76	22.22	21.53	18.28
B23t.	15 - 31	1.32	32.02	29.26	28.67	27.27	24.58
B31	31 - 42	1.41	29.89	28.02	25.87	21.68	18.62
B32	42 - 56	1.29	35.15	26.66	19.52	16.49	13.02
C	56 - 71+	1.29	36.36	24.46	26.29	15.78	10.69

Figure 3.–Hydrologic zones of land-capability classes.

Table 3.–Hydrologic capacities of soil texture classes

[Adapted from "Land Capability: A Hydrologic
Response Unit in Agricultural Watersheds," by C. B.
England, Res. Soil Scientist, USDA Hydrograph
Laboratory, Beltsville, Md. (USDA ARS 41-172,
Sept. 1970)]

Texture class	S^1	G^2	AWC^3	AWC/G
	Percent	*Percent*	*Percent*	
Coarse sand	24.4	17.7	6.7	0.38
Coarse sandy loam	24.5	15.8	8.7	0.55
Sand.	32.3	19.0	13.3	0.70
Loamy sand	37.0	26.9	10.1	0.38
Loamy fine sand.	32.6	27.2	5.4	0.20
Sandy loam	30.9	18.6	12.3	0.66
Fine sandy loam	36.6	23.5	13.1	0.56
Very fine sandy loam	32.7	21.0	11.7	0.56
Loam	30.0	14.4	15.6	1.08
Silt loam.	31.3	11.4	19.9	1.74
Sandy clay loam	25.3	13.4	11.9	0.89
Clay loam.	25.7	13.0	12.7	0.98
Silty clay loam	23.3	8.4	14.9	1.77
Sandy clay	19.4	11.6	7.8	0.67
Silty clay	21.4	9.1	12.3	1.34
Clay	18.8	7.3	11.5	1.58

[1] S = Total porosity − 15 bar moisture percent.
[2] G = Total porosity − 0.3 bar moisture percent.
[3] AWC = S minus G.

(current temperature - lower cardinal temperature)/
(optimum cardinal temperature - lower cardinal tempera-
ture) for corn and alfalfa. Cardinal temperatures are the
optimum and lower or minimum temperatures for crop
growth. When current temperature exceeds the optimum
cardinal limit, the plant is assumed to suffer and the XGI
function is set less than 1.0 by one-half of the amount of
exceedence. If current temperature is equal to or less
than the lower cardinal limit, the XGI is set equal to a
fixed minimum of 0.1.

The growth index for a given crop is then computed
from the XGI curve for that crop, as illustrated in figures
5 and 6 for corn and alfalfa respectively. The crop
growth index, GI, follows the XGI if no cultural
practices intervene. However, cultural practices that
reduce the foliage also reduce evapotranspiration; hence,
GI for the crop is reduced following plowing, planting,
cultivating, or harvesting *if vegetation is abolished or
significantly reduced* by the operation. (This excludes
minimum tillage practices.) After each practice, the crop
is assumed to recover in a specified number of weeks at
which time the GI curve rejoins the XGI curve. In the
case of turnplowing, the soil is inverted and left in an
aerated condition; hence, the GI value is set at 1.0 and
assumed to settle back to a bare fallow condition of low
ET in two weeks where it remains a constant at 0.1 until
planting of a crop.

Cardinal temperatures can be obtained from the literature for most crops. Table 4 is a compilation of upper and lower cardinal temperatures for some of the more common crops together with literature citations. Generally, the local reputation of a crop for seasonal growth can be drawn upon to approximate the cardinal limits; *e.g.,* if a grass is known to go dormant at midsummer, the associated temperatures indicate the upper limit. Winter wheat would be expected to have a lower limit near to freezing. The evapotranspiration potential can then be estimated for any given day as

$$ET = GI \cdot k \cdot E_p \cdot [(S-SA)/AWC]^x \qquad [1]$$

Table 4.—Cardinal temperatures for growth of some common crops, degrees Fahrenheit

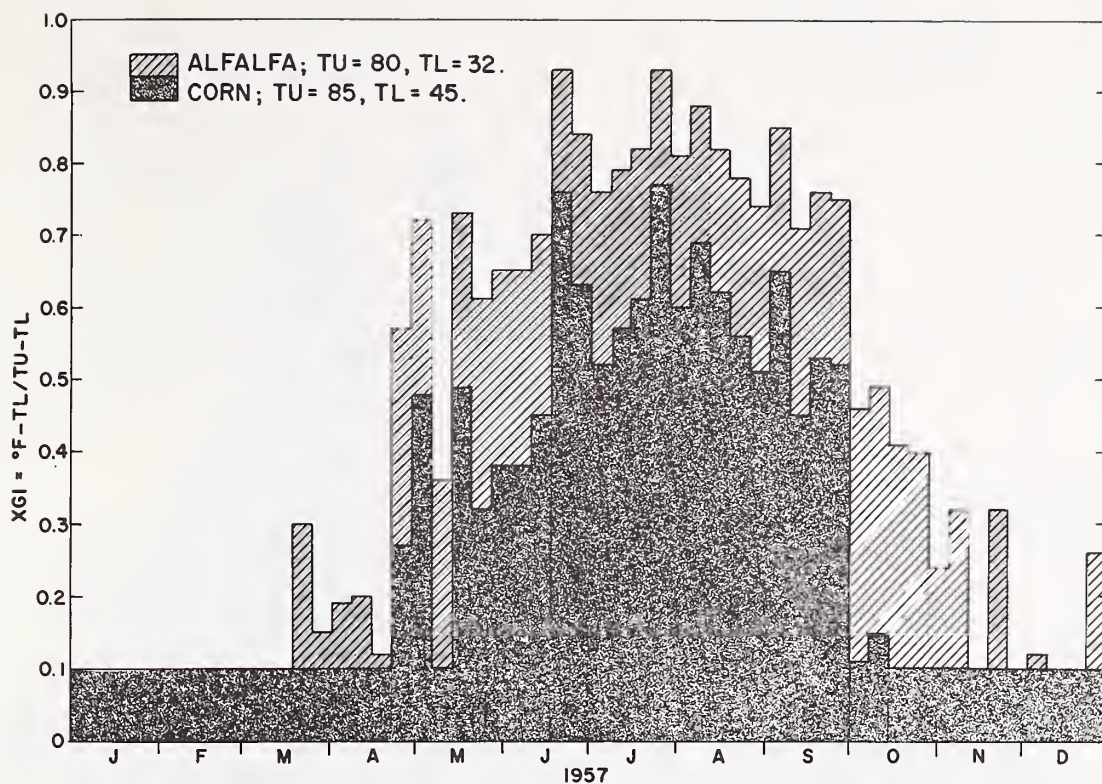| Crop	Cardinal temperatures			Reference source
	Minimum	Optimum	Maximum	
Oats, rye, wheat, barley . .	32-41	77-87.8	87.8-98.6	Parker, N. W. 1946. Environment factors and their control in plant environments. Soil Sci. 62:109-119.
Sorghum, melons	59-64.4	87.8-98.6	111.2-122	
Corn	50			Chang, J. H. 1968. Climate and Agriculture: An Ecological Survey. Aldine Publ. Co., pp. 75-76.
Peas	40			
Citrus fruit . . .	55			
Oats	40			Wiggins, S. C. 1936. The effect of seasonal temperature. . . Agron. J. 48: 21-25.
Corn	50	86-95	113	Meyer, B. S. and D. B. Anderson. 1939. pp. 589-591. D. van Nostrand Co., Inc., New York.
Corn	49	93	115	
Flax	35	70	82	Oosting, H. J. 1953. The Study of Plant Communities. W. H. Freeman & Co., San Fran., pp. 127-128.
Peas, vetch, rye	33-34			Haberlandt, 1874, cited by Richards, S. J. et al. 1952. Soil temperature and plant growth. *In* Soil Physical Conditions and Plant Growth. Agron. Mono. II: 360-363.
Corn, sorghum .	46-50			
Tobacco	55-57			
Corn			110	Lehenbauer, P. A. 1914. Growth of maize. . .Physiol. Res. 1: 247-288.
Corn	50	60-95	105	Wang, J. Y. 1963. Agricultural Meterology. Pacemaker Press, Milwaukee. pp. 104-105.
Sorghum	60			Rhykerd, C. L., et al. 1960. Sorghum grows best at warm temperatures. Crops and Soils 12:24.
Sorghum		80-84		Martin, J. H. 1941. Climate and Sorghum. *in* USDA Yearbook of Agric., p. 343.
Sorghum			100	Doggett, H. 1970. Sorghum. Longmans, Green and Co., Ltd. London. pp. 188-189.
Tobacco	60	80	100	Garner, W. W. 1946. The Production of Tobacco. Blakiston Co., Phila., pp. 376-377.
Ryegrass		60		Weihing, R. N. 1963. Growth of ryegrass as influenced by temperature. . . Agron. J. 55: 519-521.

Figure 4.—Relative potential growth (XGI) curves for corn and alfalfa computed from upper and lower cardinal temperatures (TU and TL).
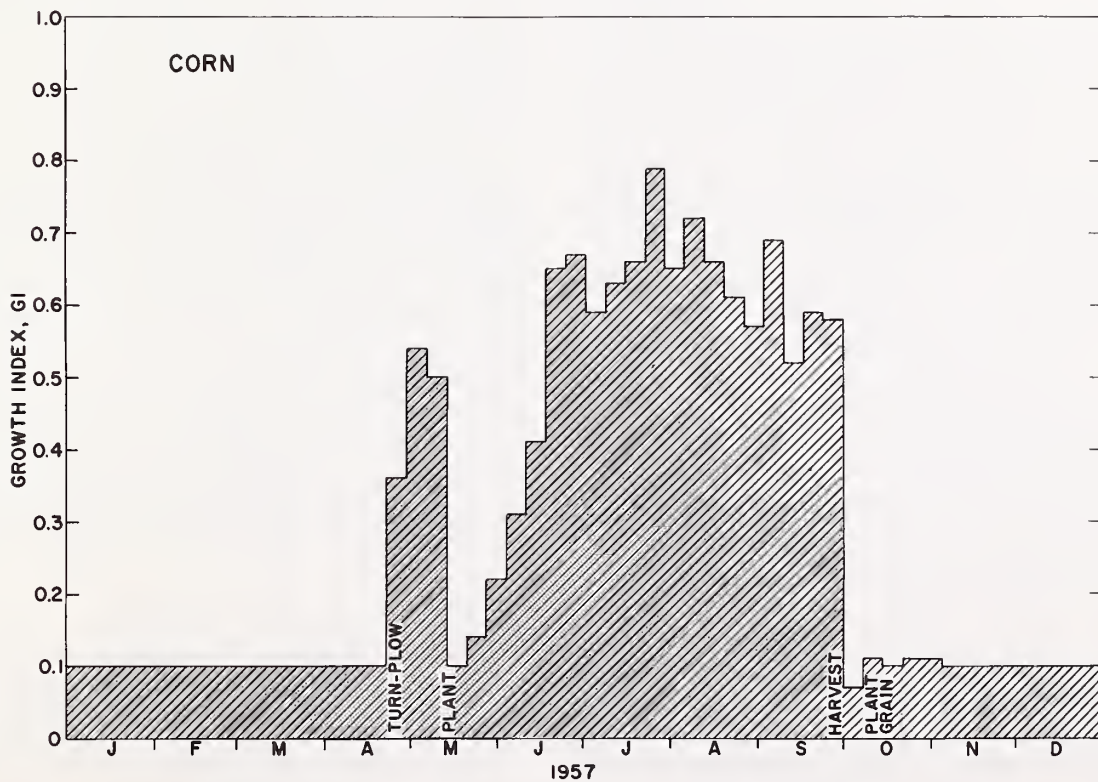

Figure 5.—Relative growth (GI) curve for corn as modified by tillage.
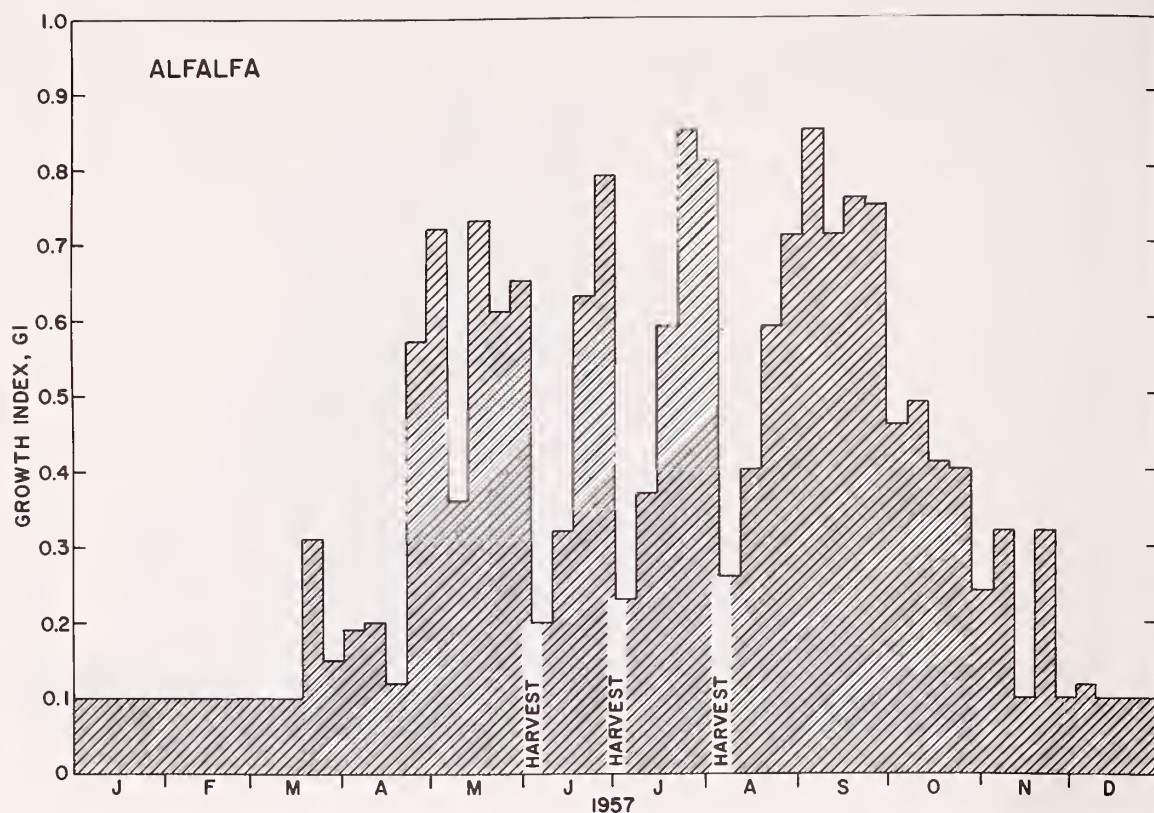
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Figure 6.—Relative growth (GI) curve for alfalfa as modified by cutting.

where

ET is evapotranspiration potential in inches per day;

GI is growth index of crop in percent of maturity;

k is ratio of GI to pan evaporation, usually 1.0-1.2 for short grasses, 1.2-1.6 for crops up to shoulder-height, 1.6-2.0 for forest;

E_p is pan evaporation in inches per day;

S is total porosity;

SA is available porosity;

AWC is porosity drainable only by evapotranspiration;

and x is set equal to 0.5 for sands and 1.0 for finer textures.

Input to the model now includes 52 weekly averages of air temperature in place of the GI curves required for each crop in Model-70. The use of temperature is designed to individualize plant growth estimates for each year.

Dr. Wadleigh, in mathematical analyses of plant growth data (unpublished), demonstrated that free water (above field capacity) dampens and inhibits plant growth, and subsequently ET, by exclusion of oxygen needed for plant growth. As illustrated schematically in figure 7, growth and, consequently, ET decreases from optimum at field capacity to zero at soil saturation. Thus ET increases from wilting point to an optimum at field capacity and diminishes to zero at saturation. However, free-water evaporation increases from zero at field capacity to a value equal to pan evaporation at soil saturation. This separation of evaporation and transpiration becomes important in chemical transport studies.

Infiltration

Infiltration capacity was expressed by Holtan (18) as an exhaustion phenomenon convergent upon some constant rate:

$$f = a \cdot S_a^{1.4} + f_c \qquad [2]$$

10

where

f is infiltration capacity in inches per hour;

a is the infiltration capacity in inches per hour per (inch)$^{1.4}$ of available storage (index of surface-connected porosity);

S_a is available storage in the surface layer (the "A" horizon in agricultural soils) in inches water equivalent;

and f_c is the constant rate of infiltration after prolonged wetting (associated with capillary flow or with an impeding stratum) in inches per hour.

The GI of equation [1] is also used as a seasonal factor on the vegetation parameter "a" in the infiltration equation [3]:

$$f = GI \cdot a \cdot S_a^{1.4} + f_c \qquad [3]$$

Infiltration and rainfall excess are computed for each soil zone by comparing observed rainfall to the infiltration capacities computed by equation [3]. In solutions of equation [3], the volume of infiltration cannot exceed the volume of water available at the soil surface (including detentions of overland flow), nor can it exceed the product of the time increment and the average rate, $(f_1 + f_2) \cdot t/2$. Infiltration capacity depends on the amount of empty space with S_a diminished by infiltrated water but recovered by drainage or evaporation to the limit of G, and by ET to the additional limit of AWC.

Values of "a" are shown in table 5 for various land uses in agriculture. These were evaluated at plant maturity as the percentage of the ground-surface area

Figure 7.—Relative growth as modified by free water (matrix suction less than .25 bars) and moisture deficit (matrix suction greater than .25 bars). (After Wadleigh, unpublished.)

Table 5.—Tentative estimates of vegetative parameter "a" in infiltration equation

$$f = GI \cdot a \cdot S_a^{1.4} + f_c$$

Land use or cover	Basal area rating[1]	
	Poor condition	Good condition
Fallow[2]	0.10	0.30
Row crops	.10	.20
Small grains	.20	.30
Hay (legumes)	.20	.40
Hay (sod)....................	.40	.60
Pasture (Bunch grass)..........	.20	.40
Temporary pasture (sod)	.40	.60
Permanent pasture (sod)........	.80	1.00
Woods and forests	.80	1.00

[1] Adjustments needed for "weeds" and "grazing."
[2] For fallow land only, poor condition means "After row crop," and good condition means "After sod."

occupied by plant stems or root crowns. Stems and root crowns are assumed to reflect the percentage of porosity in the top layer that is surface-connected by mature plant roots to form conduits for air or water. If surface continuity is achieved by incorporation or by mechanical means, the "a" value should be adjusted to represent it.

Estimates of f_c were obtained from the SCS Handbook (49) wherein major soils of the United States are grouped according to their rate of water intake after prolonged wetting. Soils are grouped in four hydrologic classes: A, B, C, and D. Musgrave (30) gives the associated rates of f_c in inches per hour: A = 0.45 to 0.30; B = 0.30 to 0.15; C = 0.15 to 0.05; and D = 0.05 to 0.00. The texture and density of the impeding layer give a clue to the selection of f_c within a group. If the impeding strata approach clay, f_c is near the lower limit of its group; for sand f_c would be near the top. Loams would indicate the midpoint f_c.

Depressions on the land surface act as reservoirs holding a volume, V_d, of water until it is dissipated by infiltration. Although generally quite small in depth (about 0.05-inch for agricultural crops), V_d is drawn upon by infiltration and subsequently refilled by rainfall for each pause in rainfall intensity. Also, certain agricultural practices such as level terraces, contoured furrows, and listed crops may be designed to give V_d depth of several inches. Musgrave and Holtan (31) give concepts and some estimates of depression storage in agriculture, but generally such estimates must be based upon personal observations.
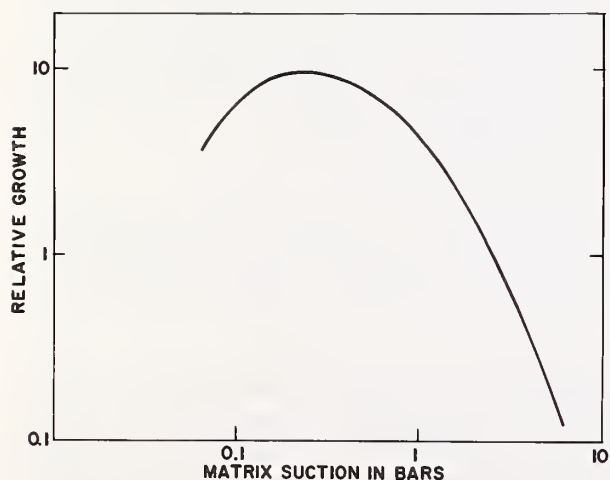
Certain soils, such as the montmorillonitic clays, form deep cracks on drying. Cracking is estimated for a given horizon from the ratio of bulk density at field capacity to bulk density when air dry by the equation:

$$\% \text{ Cracks} = 100 \left[\left(\frac{\overline{BDW}}{BDD} \right)^{1/3} - \frac{BDW}{BDD} \right] \quad [4]$$

where

BDW is bulk density at field capacity in percent volume;

and BDD is bulk density at air dry in percent volume.

This equation was developed by considering a cube of soil and by deleting vertical shrinkage. Equation [4] is applied to layer thicknesses to compute maximum cracking volumes. The volume of cracks at any given time is computed as a linear function of soil moisture present, limited to the plant available range, AWC. Cracks are therefore at maximum within the root depth at wilting point and disappear at field capacity.

Coefficients for Routing Flows

Rainfall in excess of infiltration is routed across each soil zone of figure 3 and cascaded, subject to further infiltration, across designated subsequent soil zones enroute to the channel. Overland flow is computed by an adaptation of the continuity equation:

$$Pe - Q_o = \Delta D \quad [5]$$

and

$$q_o = (ova)D^{1.67} \quad [6]$$

where

Pe is the volume of rainfall per Δt in excess of infiltration and depression storage;

Q_o is volume of outflow per Δt;

q_o is overland flow in inches per hour;

ova is a coefficient dependent upon roughness, length, and degree of slope;

D is the average depth of flow in inches;

and t is time in hours.

The coefficient "ova" in equation [6] is determined from runoff recessions on rectangular plots as described by Musgrave and Holtan. It is the rate of flow produced by an average depth of 1.0 inch of water on the plot surface. In the flow data presented by Musgrave and

Holtan, "ova" can be estimated from vegetative density "a", percent slope "S1", and feet length "Le" of flow path by the following equation:

$$ova = (150 - 125a) \cdot (12 / \sqrt{1.5}) \cdot \sqrt{S1}/Le \quad [7]$$

For laminar flow, "ova" would vary linearly as "S1" in equation [7] and the exponent, 1.67, must be changed in equation [6] to 3.0.

Channel flows and subsurface return flows are routed by simultaneous solutions of the continuity equation and a storage function. Storage coefficients are obtained by integration of the flow recession curve for a given watershed. Techniques are under study in the USDA Hydrograph Laboratory for the approximation of flow recession curves by linear segments to obtain the advantages of superposition in routing water flows from different areas of the watershed. Flow from each unit is routed separately through watershed storage, and all are summed to obtain watershed outflow.

Postrainfall recession curves are plotted on semi-logarithmic paper in figure 8 for Little Mill Creek Experimental Watershed near Coshocton, Ohio. Evapotranspiration must be minimized if we are to obtain a true storage-flow relationship. The winter (March) recession shows the least influence by ET and is used for analyses. The equation of a recession curve segment is:

$$q_t = q_o e^{-t/m} \quad [8]$$

where:

q_o is rate of flow at start of a period in inches per hour;

q_t is rate of flow one time-increment later in inches per hour;

m, the absolute value of $t/\Delta \ln(q)$, is a constant for each straight-line segment of the recession curve on semilogarithmic papers;

e is logarithmic base;

and t is the time-increment in hours.

By integration of equation [8] the storage increment, ΔS, within a linear segment of the recession curve is:

$$\Delta S = m \ \Delta q \quad [9]$$

Values of "m" derived for each linear segment of the semilogarithmic plotting are assumed to represent successive flow regimes (34), starting with m_c for channel flow and proceeding through a series—"m_1, m_2, m_3, and m_4"—for successively deeper or more devious regimes of subsurface flow. Some watersheds, such as the Hastings W-11, have no return flow; hence, only m_c is defined.
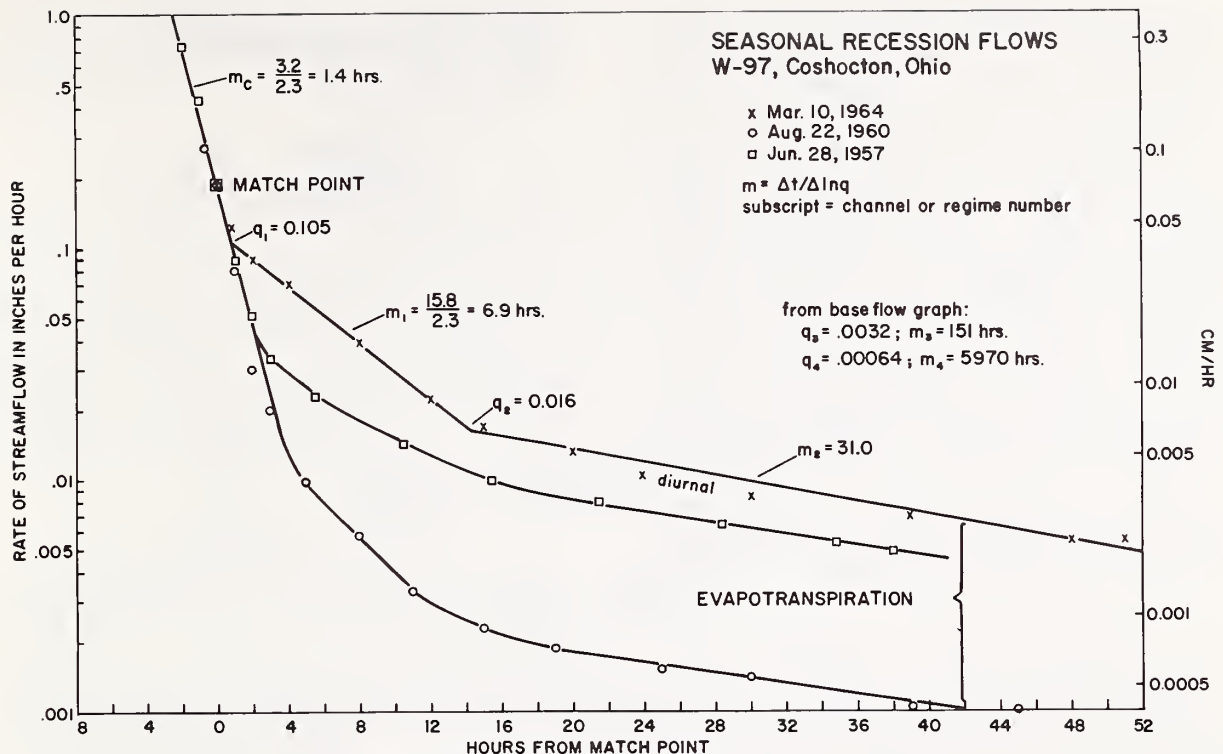
Figure 8.—Seasonal recession flows, W-97, Coshocton, Ohio.

At Coshocton, flow regimes must be separated. The usual procedure has been to extend segments *backward* in time for subtraction from earlier regimes (*3*). In our experience, and that of Kulandaiswamy and Seethorman (*27*), the adjusted points never plotted as a straight line, and the resulting recession was too rapid. The authors prefer to use the same procedure generally used for separation overlapping hydrographs of surface flows, that is, extending the recession of the first storm *forward* in time for subtraction from subsequent flows.

Figure 9 illustrates results of techniques suggested for separating flow regimes for input to this model. Each linear segment is extended toward zero and subtracted from subsequent flows to get the rising hydrograph of the succeeding regime. Now there is no question about maintaining logarithmic linearity within flow regimes. Also, the rising hydrograph fits better with the concept that return flows are less when flows in stream channels are at higher stages. The total volume of the separated hydrograph can be computed for successive subsurface regimes by the equation:

$$S = q_b (m_L - m_{L-1}) \qquad [10]$$

where:

S is total storage volume of the *difference hydrograph* in inches;
q_b is rate at intersect with the previous segment of recession;
m is absolute value of $t/\ln (q_o/q_t)$;
L is flow regime number;
and subscript L-1 indicates "m" of the previous segment.

Input to the model would then be "m_c, q_1, m_1, q_2, m_2, q_3, m_3, q_4, and m_4" for those watersheds having four discernable regimes of subsurface flow. The value of "m" is readily determined as the number of hours required for the recession segment to cross one log cycle divided by 2.3, the natural logarithm of 10.0. Maximum free-water storage is assumed equal to the "G" value from the soil survey for regimes 1 and 2, but it is the volume under the hydrograph computed by equation [10] for the remaining flow regimes as in figures 8 and 9.

M_c, as determined from the watershed flow recessions, includes detentions of overland flow. Since overland flow
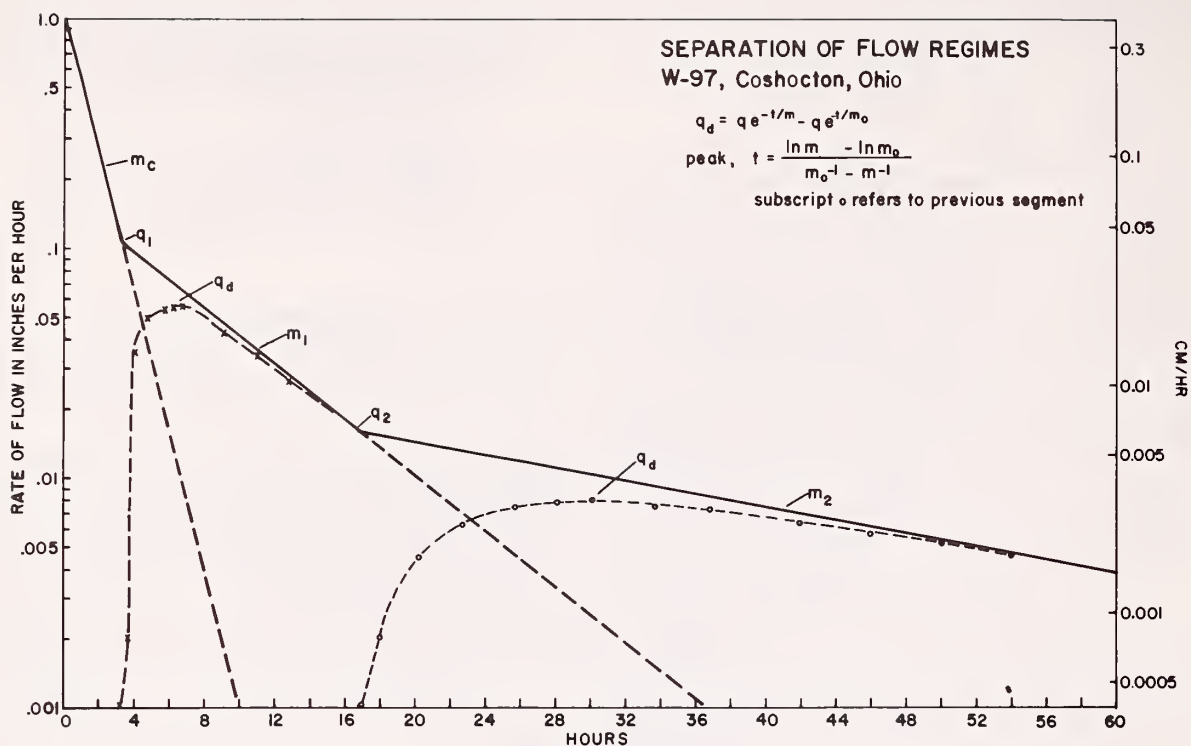
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Figure 9.–Separation of flow regimes, W-97, Coshocton, Ohio.

is routed in equation [6], the depth of overland flow must be subtracted from the ΔS of equation [9]. At the peak, outflow is essentially equal to inflow and channel storage would be:

$$S = m_c \cdot q - (q/ova)^{.6} \qquad [11]$$

We can get an approximation of the corrected m_c (cm_c in the program) by solving for m in equation [9] at one unit of flow rate:

$$cm_c = m_c - ova^{-.6} \qquad [12]$$

Equation [12] is an approximation only and typifies an area of needed research.

Concern for the transport of agricultural chemicals has placed emphasis on the path of both surface *and* subsurface flows from relatively small upland areas well above the elevation of emerging subsurface return flow. As a result, values of m_1 to m_4 are obtained from downstream gaging sites of an encompassing watershed together with an indication of the number of regimes (including m_c) which occur above the weir. Output then includes "onsite" return flow in "runoff" and lists "offsite" flows for comparison with regional information.

As the size of watershed diminishes, the importance of detail increases. Therefore, m_1 and m_2 are subscripted by zone and reevaluated from soils information. Assumptions were:

(1) Outflow is equal to permeability · width/length · gradient;
(2) permeability varies as the ratio of pore diameters squared or as the square of the ratio of large pore volumes;
(3) and, since f_c is permeability of layer 2, the permeability of layer 1 is $f_c(G_1/G_2)^2$.

Then, since storage, (FREE WATER) is equal to DEPTH/G and since m = FREE/G, we can derive mz(1) and mz(2) for each zone by equation [13].

$$mz(L) = depth\ (L) \cdot G_2^2 \cdot Le^2 \cdot (Sl^2 + 1)^{.5}$$

$$(f_c \cdot G(L) \cdot zone\ area \cdot Sl) \qquad [13]$$

If the downstream flow record indicates that the hydrograph recession passes abruptly from the characteristic surface flow hydrograph to the low, sustained baseflow without transitional slope breaks, m_1 and m_2 can be entered as zeroes. The program will not compute flows in a regime whose m value is zero.

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Equation [14] is a combination of the continuity equation and equation [9] used in computing outflow from each regime:

$$q_2 = \frac{2\Delta I}{2m + \Delta t} + q_1 \cdot \frac{2m - \Delta t}{2m + \Delta t} \qquad [14]$$

Equation [9], being linear, forces the routed hydrograph from equation [14] to peak at its crossing with the inflow hydrograph, whereas channel flow responds non-linearly to changes in inflow rate. Therefore, non-linearity was induced on the rising side of the streamflow routing by the techniques of Holtan and Overton (21) for successive routings through one-half of indicated storage using equation [15]:

$$q_2' = \frac{2\Delta I}{m + \Delta t} + q_1' \frac{m - \Delta t}{m + \Delta t} \qquad [15]$$

In the second application of equation [15] the quantity $(q_1' + q_2')\Delta t/2$ is substituted for ΔI. The symbols are:

 I is inflow volume in inches;
 m is routing coefficient in hours;
 t is increment of time in hours;
 q is rate of outflow from storage in inches per hour;
 q' is theoretical rate of outflow from first half of storage in inches per hour;
 and subscripts $_1$ and $_2$ indicate beginning and end of Δt.

Hydrogeology

In the USDA Hydrograph Laboratory's model, infiltrated water is proportioned to ET, or free-water evaporation, and to downward seepage, or to lateral return flow, in each flow regime. Downward seepage and lateral flow are supplied by free water; hence, estimates of maximum seepage rate "C" and free water capacity "G", as well as the storage coefficient "m", are needed in each flow regime.

Since subsurface flow regimes are considered sequential, seepage, C, from a given regime is inflow to the next regime and must be adequate to supply the sum of the maximum flow rate "q_{L+1}" experienced in the next regime and the rate of deep seepage, gr:

$$C = q_{L+1} + gr \qquad [16]$$

where:

 L is the regime number;
 and gr is the maximum rate of ground water recharge in inches per hour.

Ground water recharge from the ultimate return-flow regime is estimated on a regional basis. Average annual rainfall, average annual ET, and average annual stream-flow yields in the vicinity can be used to derive an average annual ground water recharge. This can be converted to inches per hour as an estimate of gr. At Hastings, this value was estimated as equal to f_c; but the estimate for the Coshocton, Ohio, watershed was 0.0006 inches per hour, and for the Texas and Florida watersheds, gr was estimated as zero.

It must be borne in mind that for small upland areas the deeper regimes may pass beneath the point of surface-flow measurement. If so, gr must be estimated equal to q_{max} of the first unmeasured regime and the q and m values of the nonoccurring regimes must be omitted.

Increments of downward seepage, "subput", to the next regime, are computed as a function of a free-water present:

$$Subput_{L+1} = t \cdot C \cdot (G - SA)/G \qquad [17]$$

The potential rate of outflow q_p from a regime is derived by equation [14], but actual outflow from a regime is held equal to zero, as illustrated in figure 9, whenever summation outflow exceeds the value of intercept q_b for that regime. When summation outflow is less than q_b, a favorable gradient is assumed and outflow q_L is computed by the following equation:

$$q_L = q_p (q_b - \Sigma_q)/q_b \qquad [18]$$

where

 q_b is intercept with previous segment;
 Σ_q is sum of all existing flow rates;
 and q_p is potential regime outflow from equation [14].

An exception to equation [18] is made for frozen ground. If the 3-week moving average air temperature is below freezing, the c of equation [17] is reduced for layer 1 by 0.02 inch per hour for each average degree Fahrenheit below 32. Thus it is assumed that highly permeable soils become impervious at lower temperatures. Since only f_c is affected, soils take in water up to saturation during low temperatures but no outflow occurs from layer 1 until temperatures rise above freezing.

The limits of free-water storage in the first two regimes are computed from soil survey data as the products of horizon thickness and percent freely drained porosity. The limit of free-water storage, G, associated

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with subsequent flow regimes is computed from the storage-flow relationship:

$$G_L = q_b \cdot (m_L - m_{L-1}) \qquad [19]$$

There is no assurance that the flow recession analyzed represents a saturated A or B horizon. Hence, the G-values determined from soil survey data for these two horizons take precedence in the model. Subsequently, the q-values and the G-values of regimes 3 and 4 are apportioned to each zone of the watershed in proportion to the free-water limit "G" of the topsoil:

$$G_3 \text{ (zone)} = m_3 \cdot q_{max_3} \cdot G_1 \text{ (zone)}/\bar{G}_1 \qquad [20]$$

where $\bar{G}_1$ is a weighted watershed average from soil survey.

By this means the storage indicated by the lower flow recession is dispersed over the watershed in proportion to the depth of the topsoil horizon in each zone or hydrologic response unit. Routing coefficients, m_3 and m_4, remain unchanged for each regime, but the storage potentials, G_n, and the maximum outflows, q_{max}, are now unique for each zone.

$$q_{max} = G/m \qquad [21]$$

Evapotranspiration is drawn from both G and AWC when roots are present. Geologic research is needed to develop concepts of flow regimes associated with specific depth in the profile. In the meantime, we are placing greatest reliance on soil surveys for storages of regimes 1 and 2 and depend on the recession curve analyses for storage values of subsequent regimes. Roots are arbitrarily designated as drawing water from the first two regimes, often creating a deficit in AWC to be satisfied before accruals to subsequent regimes can occur. Therefore, AWC_1 and AWC_2 are required input. AWC_1 is obtained from the moisture tension data of the first layer. AWC_2 is estimated from the moisture tension data below the first layer to the depth of suitable habitat for roots as indicated in the soil profile description. Moisture deficits are computed only in the depth indicated for root habitat. Today, there is no basis for distributing any part of AWC to subsequent regimes except in a few places like Florida where records of wells over impervious rock at very shallow depths may permit some speculations.

Evaporation from free water in the soil is treated as a function separate from evapotranspiration. It is extracted from the sum of free water "G" in regimes 1 and 2 as the product of percent total free water available and pan evaporation.

A percentage of overland flow from each zone is designated to cascade across the subsequent soil zone, with the remainder, if any, allocated to the alluviums or directly to channel inflow. Allocation is a matter of judgment based on the nearness of a zone to alluviums or upon the presence or absence of diversions, graded terraces, listed furrows, or other interceptors leading directly to a stream channel. Infiltration in excess of AWC in the root zone is routed through storage of subsequent regimes and accumulated as run-on to the alluvium or as direct inflow to the stream channel if so designated by input. The total of all inflows to the channel is routed, using the channel storage coefficient m_c in equations [13] and [15] to obtain the outflow hydrograph for the watershed.

The Erosion-Deposition Submodel

"A Watershed Sediment Yield Model with Hydrological and Chemical Interfaces"

This submodel predicts components necessary for the erosion-chemistry interface. It simulates the erosion-deposition continuum for watershed slopes on an area basis. This phase is subdivided to estimate the interrill and rill erosion components of the total sediment load. Particle size distributions of the eroded material are also estimated for erosion-chemistry relations. Each calculation utilizes hydrologic input together with basic soil parameters for each compartment of the watershed transformation.

Basic Equation

The conceptual basis for the erosion and sedimentation submodel is the Universal Soil Loss Equation (USLE):

$$A = RKCPSL \qquad [22]$$

where

A = estimated soil loss (T/ac)
R = rainfall factor
K = soil erodibility factor
C = cropping management factor
P = erosion control practice factor
S = slope steepness factor
L = slope length factor

The S and L factors can each be expressed mathematically based on data analyses by Wischmeier and Smith (*55*).

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$$S = \frac{0.43 + 0.30s + 0.043s^2}{6.613} \qquad [23]$$

$$L = (\lambda/72.6)^{0.5} = \frac{\lambda^{0.5}}{8.521} \qquad [24]$$

where

s = percent slope
λ = slope length

The USLE is widely used, and each of the factors has been determined for many soils and situations throughout the United States. It was originally derived to predict average annual soil losses. However, all factors can also be evaluated on a storm basis. Throughout this report, it is being used on a storm basis. In the USLE, the energy available for detachment is that derived only from raindrop impact.

Williams (53) has modified the USLE to predict sediment yield, G, at the watershed outlet. The rainfall energy term was replaced by an empirically derived term based only on flow characteristics for a particular storm event.

$$G = \frac{\alpha(Qq_p)^\beta}{A_r} \, KCPSL \qquad [25]$$

where

G = sediment yield (T/ac)
Q = runoff volume (ac-ft)
q_p = peak flow rate (cfs)
A_r = drainage area (ac)
α, β = coefficients

K, C, P, S, L = USLE factors

The coefficients, α and β, determined from 778 events on 18 watersheds in Texas and Nebraska, were 95 and 0.56 respectively (53). The coefficients, calculated from data by Piest, et al. (37) from 103 events on two Iowa watersheds were found to be 23.6 and 0.65, respectively. The exponents are nearly equal, indicating that a change in the product, Qq_p, has about the same effect. However, location differences are revealed more significantly by differences in α.

The USLE and the Williams modification represent the two extremes with regard to energy required to initiate detachment, in that one utilizes rainfall energy entirely and the other, runoff entirely. Both rainfall and runoff have detachment potential and act simultaneously at times during a rainstorm. The relative influence of each is dependent on both time and space in a watershed.

At the beginning of a storm, before runoff begins, raindrop splash is detaching and transporting soil. This is the major energy source since runoff has not begun. When runoff begins, it also has potential that increases with the rising hydrograph. At the end of the storm, runoff is the detaching and transporting agent.

With regard to position on a watershed, upslope erosion, where detachment is limiting, depends primarily on rainfall energy and slope gradient (54). Splash action and sheet flow transport the soil particles to flow concentrations or rills. Downslope, as runoff increases, its detachment and transport potential increases relative to rainfall. Finally, transport capacity becomes limiting and sediment yield becomes closely related to the hydraulic properties of the runoff and less related to rainfall characteristics (10a).

Foster (10a) modified equation [1] to reflect both rainfall and runoff contributions.

$$A = [aR + bcQq_p^{1/3}] \, KCPSL \qquad [26]$$

where

a,b = weighting parameters (a+b=1)
c = equality coefficient
R = rainfall factor
Q = runoff vol. (in.)
Q_p = runoff rate (in./hr.)
K, C, P, S, L = USLE factors

The weighting parameters reflect the relative amounts of erosion caused by rainfall and runoff under unit conditions (L, S, C, P = 1). Limited experimental evidence (56, 28) indicates that the detachment is about evenly divided under these conditions (i.e., a = b = .5). The equality coefficient, c, can be estimated from rainulator plot data under unit conditions.

$$c = (2A_u/K - R)/Qq_p^{1/3} \qquad [27]$$

where

A_u = soil loss under unit condition.

Analysis of 55 unit rainulator runs on 20 soils in Indiana[7] and Minnesota shows that c equals 29.3 or

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[7]Foster, G. R. 1973. Personal communication.

approximately 30. Substituting these values of a, b, c into equation [26] yields the basic equation for the erosion-deposition submodel.

$$A = EKCPSL \qquad [28]$$

where

$$E = 0.5R + 15Qq_p^{1/3}$$

The coefficients, a, b, and c, may be dynamic in that they may change from time to time and place to place on a watershed during a storm. They may also be different during the detachment and transport phases of erosion. So might the other factors in the USLE. However, formulations of these relations cannot be made at this time due to lack of data. Therefore, throughout the succeeding discussion, it is assumed that these coefficients and the USLE parameter remain constant at their indicated values through time and space and also for both phases of the erosion process.

Detachment Component Development

For a field of uniform slope, s, as shown in figure 10, equations [24] and [28] are combined to give:

$$A = \frac{EKCPS \, \lambda^{0.5}}{8.521}$$

This can be extended to any point x on the slope so that

$$A = \frac{EKCPS \, x^{0.5}}{8.521} \qquad [29]$$

When the soil loss is expressed as lbs/foot of width, equation [29] becomes

$$A' = \frac{EKCPS \, x^{1.5}}{185.58} \qquad [30]$$

Foster and Wischmeier (10) have shown that the detachment rate at any point x is

$$D_x = \frac{\partial A'}{\partial x} \qquad [31]$$

or from equation [30]

$$D_x = \frac{EKCPS \, (1.5 \, x^{0.5})}{185.58} \qquad [32]$$

Integration of equation [32] between two length limits yields the detached soil capacity for the length segment. So, for segment j of the complex slope shown in figure 11

$$A_{dj} = \int_{x_i}^{x_{i+1}} D_x \, dx \qquad [33]$$

where A_{dj} = detached soil capacity for segment j or

$$A_{dj} = \frac{E_{x_{i+1}} K_j \, C_j \, P_j \, S_j}{185.58} (x_{i+1}^{1.5} - x_i^{1.5}) \qquad [34]$$

where

$$E_{x_{i+1}} = 0.5R_j + 15Q_{x_{i+1}} (q_{px_{i+1}})^{1/3}$$

When this is extended to a compound slope having n segments, the cumulative detached soil capacity is

$$A_t = A_{d1} + \cdots + A_{dj-1} + A_{dj} + A_{dj+1} + \cdots + A_{dn}$$

This would equal the sediment yield per unit width if no deposition occurred along the slope length. Alternatively, the sediment yield equals the cumulative detached soil capacity provided the transport capacity is not limiting.

Figure 10.–Field of uniform slope.

Figure 11.–Complex slope profile.

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Transport Component Development

For a uniform slope, let the USLE represent the transport capacity at any point x, so that

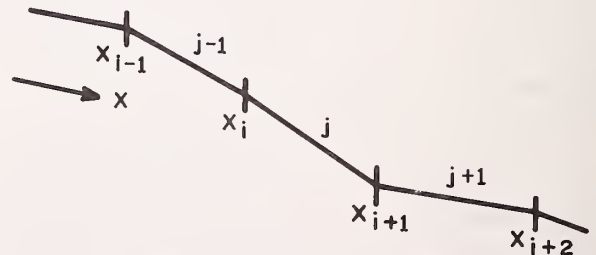$$A_{cx} = \frac{E_x\,CKPS}{185.58}\,x^{1.5} \qquad [35]$$

where

$$A_{cx} = \text{transport capacity at x}$$

This assumes that C, P, and S remain constant and identical to those for detachment in the transport phase. The value of K should reflect the transportability of the material coming from upslope and the effect of soil properties on rilling and transport capacity on downslope segments. Therefore, an effective value, $\overline{K}$, is used which is the average K of the upslope segments. For a nonuniform slope, the transport capacity for any segment is assumed to be that sediment load calculated using the total slope length for L and the slope steepness of the segment for calculation, S. Referring to figure 11, the transport capacity at x_{i+1} is

$$A_{cx_{i+1}} = \frac{E_{x_{i+1}}\,C_j\,\overline{K}\,P_j\,S_j}{185.58}\,x_{i+1}^{1.5} \qquad [36]$$

assuming a slope steepness of s_j throughout the length x_{i+1}.

Therefore, two cases can exist for slope segment j (i.e., at x_{i+1}).

Case 1

If $A_t \leq A_c$, erosion occurs on slope segment j because the transport capacity exceeds the total detached soil. Therefore, the sediment yield $G = A_{d1} + \cdots + A_{dj-1} + A_{dj}$ and the deposition M = 0.

Case 2

If $A_t \geq A_c$, deposition occurs on slope segment j because total detachment exceeds the transport capacity. Therefore, the sediment yield $G = A_{cx_{i+1}}$ and the deposition $M = A_t - A_{cx_{i+1}}$.

Rill-Interrill Contributions

The division of soil loss between rill and interrill areas is important for the chemical-sediment interface because of different methods of chemical application. For example, a chemical application tilled-in would have a different contribution from another applied as a spray.

The conceptual basis for the rill-interrill contributions are separate laboratory studies conducted by Young (56) and Meyer, et al. (28) in which they observed the trends illustrated in figure 12. The top part of the figure shows that the interrill erosion rate builds up rapidly and then abruptly levels off, indicating that the rate remains constant downslope. The bottom part indicates that at some distance downslope rill erosion volume equals interrill erosion volume and, again, that interrill erosion increases linearly. Furthermore, when interrill and rill erosion volumes are equal, interrill erosion rate has already become constant.

Foster[7] derived a relationship which approximates the ratio of rill erosion to interrill erosion for a segment where detachment rate is at capacity.

$$\beta_j = \frac{(x_j^2 - x_{j-1}^2)\,(0.043s_j^2)}{72.6(X_j - X_{j-1})\,(0.3s_j + 0.43)}$$

$$\left(\frac{K_r}{K_i}\right)_j \left(\frac{15Qq_p^{1/3}}{0.5R}\right)_j \qquad [37]$$

where s = percent slope and
K_r/K_i = ratio of rill to interrill soil erodibility (rillibility).

Rough guidelines for the ratio, K_r/K_i, are:
$K_r/K_i = 2$; "severe rilling"
$K_r/K_i = 1$; "moderate rilling"
$K_r/K_i = 0.5$; "little evidence of rilling"

In general, β increases as slope length, steepness, rillibility and runoff increase.

The quantity of sediment detached by rill erosion on a segment is

$$RA_j = A_{dj}\,\beta_j/(\beta_j + 1) \qquad [38]$$

and the quantity detached by interrill erosion on a segment is

$$IA_j = A_{dj}/(\beta_j + 1) \qquad [39]$$

The equations for cumulative rill erosion and interrill erosion in a compartment are:

$$RA = \sum_{j=1}^{m} RA_j \quad \text{and} \quad IA = \sum_{j=1}^{m} IA_j \qquad [40]$$

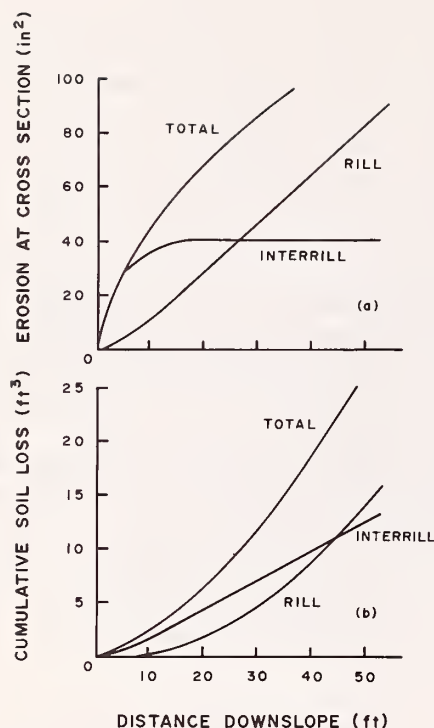where m is the number of slope segments.

Figure 12.—Eroded soil apportioned between rill and interrill sources for rill-susceptible Plot R-3. (From Meyer et. al. (28).)

The interface to the chemical submodel requires that rill surface area and depth be specified. Limited experimental evidence obtained by Foster[7] on rainulator plots indicates that the percentage of the surface intercepted by rills at various cross-slope transects remains relatively constant from the top to the bottom of the slope, although the number of rills becomes less in the downslope direction. Based on these data and other data from construction site erosion, he postulates that the average rill width can be represented as follows:

$$w = 2.4 \left(\frac{K_r}{K_i} \right)^{0.3} \left(\frac{s}{6} \right)^{0.3} \qquad [41]$$

where

w = average rill width (in./ft.)

This indicates that the rill width depends on the rillibility of the soil, K_i/K_r, and the slope steepness, s. As rillibility and slope steepness increase, the average rill width increases.

Average rill depth can be calculated by using the results of equations [40] and [41] and utilizing the fact that 1 yard^3 of soil weighs about 1 ton assuming the bulk density of 1.2.

$$RD = \frac{324 \, (RA)}{w\lambda} \qquad [42]$$

where RD = rill depth (in.)

Eroded Material Particle Size Distribution

It is important that not only the total amount of sediment be predicted, but also the composition of eroded material should be known for the sediment-chemistry interface. This problem was approached utilizing texture information from 56 Midwest soils. The original soil textures ranged from sand to silt loam to clay. The data consisted of measured soil loss and textural classification of both the soil matrix and the eroded material. This was done for each of two rainulator runs on four replications for each soil.

For purposes of analysis, the following specific surfaces were assumed (17):

clay — 200 m^2/g

silt — 40 m^2/g

sand — 0.5 m^2/g

Therefore, the specific surface for a particular soil, i is

$$SS_i = 200 \, (\% \, Cl) + 40 \, (\% \, Si) + 0.5 \, (\% \, Sa) \qquad [43]$$

The clay ratio can also be calculated by

$$CR_i = \frac{\% \, Cl}{\% \, Si + \% \, Sa} \qquad [44]$$

Figures 13 and 14 show the graphs of the specific surface and clay ratios of the soil matrix versus those for the eroded materials for the 56 Midwest soils. The regression equations are as follows:

$$SS_e = 14.6 + 0.84 \, SS_m \qquad [45]$$

and

$$CR_e = 0.021 + 1.08 \, CR_m \qquad [46]$$

where the subscripts m and e refer to soil matrix and eroded material, respectively. The coefficients of determination for equations [45] and [46] are 0.81 and 0.82, respectively. Equations [43]-[45], together with the fact that the sum of the components equals 1, constitute the estimation procedure. This is a first approximation recognizing that many factors are not included. It is illustrated by the following example.

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Example: Estimate the mechanical composition of the eroded soil if the composition of the soil matrix is

$$Cl_m = 20\% \quad Si_m = 40\% \quad Sa_m = 40\%$$

From equation [43]

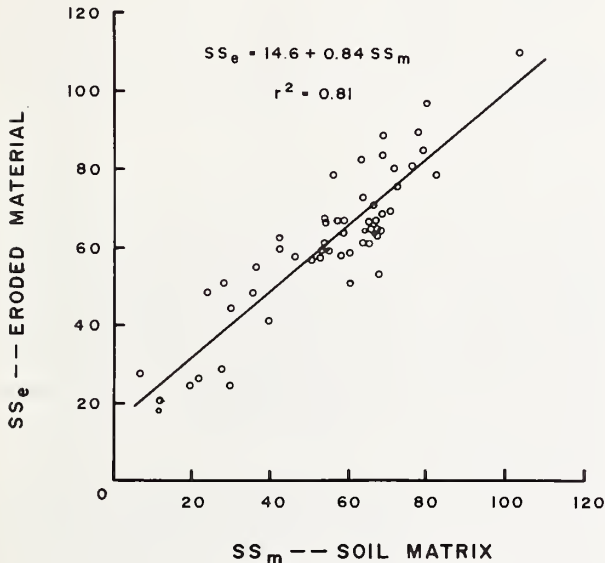$$SS_m = 200(0.20) + 40(0.40) + 0.5(0.40) = 56$$

and equation [44]

Figure 13.–Plot of specific surface; eroded vs. soil matrix.

Figure 14.–Plot of clay ratios; eroded vs. soil matrix.

$$CR_m = \frac{0.20}{0.40 + 0.40} = 0.25$$

From equations [45] and [46] the estimated parameters for the eroded materials are:

$$SS_e = 14.6 + 0.84(56) = 62$$

$$CR_e = 0.021 + 1.08(0.25) = 0.29$$

Therefore, solving the following three equations for the eroded soil textural components

$$200\,Cl_e + 40\,Si_e + 0.5\,Sa_e = 62$$

$$\frac{Cl_e}{Si_e + Sa_e} = 0.29$$

$$Cl_e + Si_e + Sa_e = 1$$

show that the estimated eroded soil compositions are

$$Cl_e = 22\%$$

$$Si_e = 43\%$$

$$Sa_e = 35\%$$

and the enrichment coefficient is

$$EC = \frac{Cl_e}{Cl_m} = \frac{22}{20} = 1.10 \qquad [47]$$

Watershed Calculations

The erosion-deposition submodel is applied to the watershed utilizing the transformation illustrated in figure 2. Each compartment may have a unique set of parameters required for the solution of the erosion-deposition equations. Calculations proceed from the top, downslope to the channel, continuing from one zone to the next. It is assumed that all soil delivered to the channel reaches the watershed outlet.

The hydrologic submodel predicts the flow volumes and discharge rates from each zone but not from each compartment. Apportionment of flow volumes and peak discharge rates among the compartments within a zone were made using linear interpolation. The same technique was used for adjacent compartments between zones. Because the zone is the smallest calculation unit permitted by the hydrologic submodel, all hydrologic input variables are identical for compartments traversing the slope. Input variable differences along the slope can

be handled by adding more zones to the hydrologic model.

The Chemical Submodel for ACTMO

"A Model of Chemical-Soil-Water Interactions"

The objectives of the chemical submodel are to calculate concentrations of a chemical in runoff, the total amount of the chemical leaving the watershed, and the location of the remaining chemical, so that management practices can be selected to minimize undesirable movement. The submodel traces the movement of a single application of a chemical through and over the watershed. Cultivation is the only management practice explicitly accounted for since it redistributes the chemical. All other practices such as contouring and terracing are implicitly handled through the hydrology and erosion submodels. Nitrate behavior was judged to be unique enough to warrant a separate submodel that uses many of the features in the general model.

Simple chromatographic theory is used to describe the leaching of the chemical and to provide a method of calculating surface concentrations for runoff and erosion. Chemicals are degraded or lost, redistributed by cultivation, and nitrate is mineralized and taken up by the crop during the period of time between storms. During the storm period the chemicals are transported by water and sediment. Adsorption characteristics of chemicals range from highly adsorbed to no adsorption. Highly adsorbed chemicals, such as DDT and phosphate, have very low solution concentrations and are moved principally by eroding the soil on which they are adsorbed. Other chemicals, such as nitrate, are not adsorbed and move with the water. Chemicals with intermediate degrees of adsorption are moved by both vehicles.

The multitude of chemical reactions in the watershed are classified into three groups: adsorption or the distribution of the chemical between the solid and the solution phases, breakdown or loss of chemical, and the dispersion of the chemical as it moves through the soil. Each of these three groups of reactions is described by a simple relation which in many cases is only a crude approximation. More complete descriptions require information not generally available.

The compartment is the basic unit for computations. The hydrology submodel divides the watershed into zones while the erosion submodel creates routing tubes to carry the cascading water and sediment across the zones to the channel. The compartment is the soil profile of each zone within a routing tube shown in figure 2 of the watershed transformation section. For purposes of chemical transport, the hydrology submodel is limited to a single crop per zone and assumes the soils are similar within a zone. Although not essential, the layers of chemical interaction with the soil are assumed to be the same as the hydrologic layers. The English units, such as pound, acre, and inch, are used. A bibliography of chemical interaction and chemical transport (Appendix) has been compiled during the development of this submodel. These papers should be of assistance to anyone wishing to estimate the parameters for a given chemical and soil or those wishing to modify any concept used in this model.

The Chemical Option

Adsorption.—The adsorption relation is assumed to be a linear isotherm,

$$S = AC \cdot C \qquad [48]$$

where S is the pounds of chemical adsorbed per pound of solid, C is the pounds of chemical per pound of solution, and AC is the adsorption coefficient. Batch equilibrations and column leaching studies (Appendix) provide information on the magnitude of the adsorption coefficient for many soils. The model can be easily changed to include nonlinear relations, but this requires another parameter.

Rates of chemical adsorption and desorption (26) were considered to introduce more complexity than is merited for this simple model. Nonequilibrium conditions cause the chemical distributions to be asymmetrical and are probably more prevalent in the real world than not. However, it would appear that this effect is usually not any larger than the normal variability encountered in the field (40, 41).

Breakdown.—There are numerous papers (Appendix) on the breakdown, degradation, loss by volatility, and persistence of chemicals in both laboratory and field conditions. A simple first order rate equation was chosen to represent these many processes. The chemical remaining, A #/a, is related to the initial amount, AA #/a, by an exponential function (EXP) of time, TI days,

$$A = AA \cdot EXP(-BC \cdot TI) \qquad [49]$$

The rate coefficient, BC/day, is dependent upon the environment around the chemical (5). There isn't enough quantitative information available at this time to make the necessary corrections, but the model has been designed to accommodate the calculations when the relations are developed. The average temperature and soil moisture are available from the hydrology submodel.

The type of application, banding or broadcasting, also changes the degradation rate (6) as can repeated applications of the same chemical (16). Such factors have been neglected in this first approximation. Large amounts of pesticides can be lost by volatilization during application and, therefore, the amount at the start of the simulation is not the amount leaving the applicator, but rather the amount that actually reaches the soil. Volatilization loss after the chemical reaches the soil is usually significant only if other losses are small. Volatilization is a complex process involving a number of factors, and this first version assumes that these losses will be reflected in the apparent breakdown coefficient. A detailed discussion of pesticide volatilization is given by Spencer et al. (43).

Dispersion.—When a chemical is carried through the soil by flowing water, there is a broadening of the chemical band and a decrease in the peak concentration. Two processes are in operation: diffusion and dispersion. Diffusion is the movement of the chemical from areas of high concentration to areas of low concentration. Hydrodynamic dispersion is the result of unequal water flow through the different sized pores and cracks in the soil and should reflect the aggregate size (36) and the ratio of porosity to permeability (4). The dispersion coefficient has the same units as the diffusion coefficient (area/time) and is proportional to the waterflow velocity. For the flow rates during infiltration and drainage, the dispersion coefficient is considerably larger than the diffusion coefficient. A more useful factor for the equations to be used is the ratio of the dispersion coefficients and the average flow velocity. For the sake of clarity this is called the dispersion distribution coefficient, DC, with units of length.

Equations involving dispersion are mathematically similar to diffusion equations where many solutions are available (24). Some experimentally measured values of DC from column studies range from .03 inch with sieved soil (7) to about 5 inches with undisturbed soil columns (14). Little field information is available for this parameter.

Movement.—There are basically two ways to calculate the movement of a chemical through the soil. The first is the finite element method in which the soil is divided into thin layers of soil (9, 12). The second is to assume a simple continuous chromatographic process. In the first method the chemical is moved from one layer to another and complete mixing with uniform distribution within a layer is assumed. Two problems arise with this approach. When the chemical is applied in a narrow band, a large number of layers are needed to accurately trace the chemical movement. The second problem is to define the thickness of the soil surface—runoff interface. The

ratio of the watershed surface area to the specific surface area (area/area per unit weight of soil) is one estimate of the amount of soil in this interface (23), but this appears to be a considerable underestimate.

An effort was made to circumvent these problems by assuming an idealized bell-shaped distribution or plug distribution for use in a simple chromatographic process. This assumption of a known mathematical equation provides a means to calculate the concentration at any depth including the surface of the soil. It appears that such a procedure is adequate when there is no adsorption or the adsorption isotherm is linear. This holds for nitrate, phosphate, and many pesticides, but not for cation exchange involved in salinity movement (39).

Water moves the chemical through the soil along several paths. The infiltrating water tends to move the chemical vertically and sometimes laterally through the soil. Runoff water carries some chemical with it and also causes erosion which can carry additional amounts of chemicals. Table 6 gives an outline of the calculations made in linking chemical characteristics with the movement of the carrier. Two types of chemical applications are provided for on the surface or mixed into the soil. The amount applied is assumed to be corrected for application losses. The surface application includes the amount on the plant surface, if any, that is readily washed off. A major gap exists in the understanding of factors controlling the rate of washoff from the plant surfaces. Mixing the chemical into the surface soil is assumed to result in an ideal uniform plug-type distribution even though this may not always be true.

Table 6.—Outline of steps for tracing chemical movement

1. Amount of loss before the storm.
2. Movement by infiltration.
3. Concentration at the surface.
4. Runoff.
5. Interrill erosion.
6. Rill erosion.
7. Accumulation and transport of water, sediment, and chemical along routing tubes.
8. Deposition.
9. Lateral outflow.
10. Mixing of water, sediment, and chemical from other tubes.
11. Location of the remaining chemical.

Losses before storms, step 1.—The chemical is lost according to equation [49] for the period of time from application until the first storm and between storms thereafter. The time-average soil moisture and temperature are available for this period and could be used to modify the amount of breakdown or loss. An extra coefficient for the photodecomposition rates at the surface is used in the array of breakdown coefficients.

Infiltration, step 2.—A great deal of information has been developed about the infiltration process (15). Since it was decided to make this first attempt a very simple model, the leaching process was divided into two stages. The first stage is prior to runoff when nonadsorbed chemicals like nitrate and halides move with the water front into dry soil (35). This distance is approximately the amount of infiltration in inches, IN, divided by the volumetric field capacity, FC.

$$D = IN/(FC+BD \cdot AC) \qquad [50]$$

The term (BD·AC) accounts for the chemicals lagging behind the waterfront when the chemical is distributed between the water and the soil of bulk density BD (13). Some anions like nitrate are excluded from some of the fine pores in the soil, and BD·AC can be given a negative value corresponding to the water volume from which the anions are excluded (42). The term field capacity is used as an operational definition of the amount of water remaining after saturated flow has ceased. It is recognized that this is physically imprecise and difficult to evaluate.

In this model the second stage of leaching is for the infiltration that occurs during runoff. There is considerable data showing that continuous percolation is less efficient in leaching salts than intermittent flow. This inefficiency is probably a result of relatively more water moving through large pores than small ones. An examination of the data in Miller et al. (29) shows that the inefficiency is proportional to the water content above field capacity. Therefore, the leaching efficiency used is the ratio of field capacity to the average moisture content during this period. The average moisture content is calculated as halfway between field capacity and saturation since the process of reaching saturation and the return to field capacity accounts for the bulk of the water movement. The depth of chemical movement, D inches, is calculated by

$$D = \frac{IR}{FC} \cdot \frac{FC}{AM+BD \cdot AC} \qquad [51]$$

where IR is the inches of infiltration during runoff, AM is the average moisture content, and the other variables have been defined.

Experimental evidence has been obtained to verify some of these relations. Figure 15 illustrates the behavior of surface-applied salts during infiltration on soils of different moisture contents (unpublished data from Durant, Oklahoma). Lithium bromide salt was applied to the surface of columns of a Fort Collins silt loam soil and then sprinkled with one inch of water at the rate of

1/4 in/hr. When the soil was air dry, the bromide, which is leached similar to nitrate, moved with the water front and was found at a depth of 4 inches in a sharp band. When the soil was wet at nearly field capacity, the simulated rain soon ponded and suction was used to draw the water through the soil. In this case there is a loss of leaching efficiency and a more dispersed band is found at a depth of 2.5 in. Lithium is a slightly adsorbed chemical with an adsorption coefficient of about three in these experimental conditions and thus is moved only about one-tenth of the bromide distance. This distance is too small to show any effect of the wet or dry treatment.

The concept being used for leaching efficiency and dispersion was tested for field conditions with published data of Miller et al. (29). Potassium chloride was applied to small plots and leached using three irrigation treatments: continuous ponding, successive 6-inch increments, and successive 2-inch increments. The chloride content of the water at different depths was monitored with porous cups and soil water by tensiometers. The dispersion distribution coefficient was calculated from all the peak concentrations relative to the distance they had moved. The calculated peak location, height, and width are compared with five sets of observed data in figure 16. The fit with other observations is equally good which suggests that the relations used should be adequate for the first approximation model being developed.
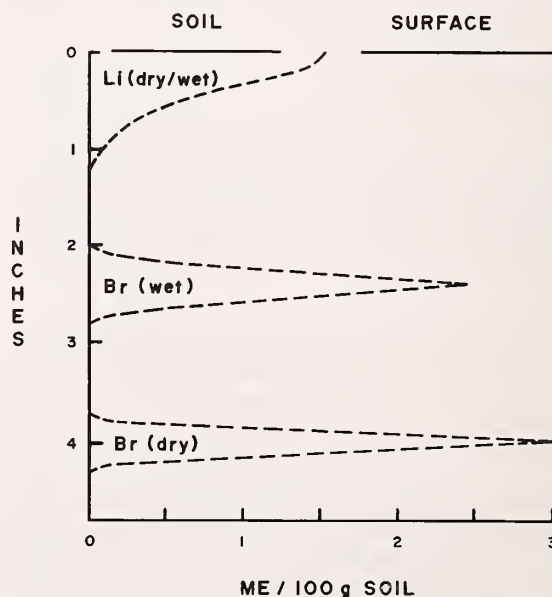

Figure 15.—The movement of lithium bromide through a column of Ft. Collins silt loam by one inch of simulated rain when the antecedent moisture was air dry or at field capacity.

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Concentration at different depths and times, step 3.—The combination of simple chromatographic behavior with dispersion and a Gaussian or bell-shaped distribution gives rise to equation [52] from which the solution concentration, C ppm, at any depth (X inches) can be calculated.

$$C(x) = \frac{A \cdot U}{\sqrt{4\pi \cdot DC \cdot D}} \, EXP \, -\left(\frac{D-X}{\sqrt{4 \cdot DC \cdot D}}\right)^2 \qquad [52]$$

A is the amount of chemical and U is a units factor equal to $4.42/(SM + BD \cdot AC)$ when A is in pounds per acre and C is in ppm at a volumetric moisture content of SM. When X = 0, the equation gives the concentration at the surface and for X = D the peak concentration in the soil is calculated.

When the chemical is mixed into the soil AP inches deep and there is infiltration that moves the plug downward D inches, the boundaries of the plug are dispersed in a sigmoid pattern (33). The concentration at X inches from the middle of the plug is given by (24):

$$C(X) = 1/2 \, CI \cdot \left[ERF\left(\frac{1/2 \, AP + X}{\sqrt{4 \cdot DC \cdot D}}\right) \right.$$

$$\left. + ERF\left(\frac{1/2 \, AP - X}{\sqrt{4 \cdot DC \cdot D}}\right) \right] \qquad [53]$$

where ERF is the error function and CI is the initial uniform concentration in ppm:

$$CI = A/(.3333 \, AC + .2266 \, SM)AP \qquad [54]$$

with .3333 million pounds of soil per acre inch and .2266 million pounds of water per acre inch. Equation [53] is used to calculate the concentration at the surface, X = D + 1/2 AP, and to check if the plug distribution can be treated as a bell-shaped distribution. When the concentration at the middle of the plug X = 0 has been depleted more than five percent by the dispersion effects, then the distribution is assumed to be bell shaped.

After a number of storms the concentrations in the solution and on the solid at the surface may be reduced below a predetermined critical level, and the runoff and erosion calculations can be bypassed.

Runoff, step 4.—After the initial infiltration when the water begins to pond on the surface and runoff commences, it is assumed that the rainfall equilibrates

Figure 16.—The calculated and observed solution concentrations of chloride with depth under two irrigation treatments (Panoche clay loam, California).

with the solid phase on the soil surface. Then the concentration in the water as it moves away from the surface is the same whether it moves vertically as infiltration or laterally as runoff. Under these conditions a projected depth of leaching can be calculated with equation [51] using the sum of infiltration and runoff. The concentration in the solution at the surface, and thus in the runoff, can be calculated with the projected depth in equations [52] or [53].

The loss of the chemical to runoff should be calculated by integrating the surface concentration as the depth increases to the projected depth. No simple way has been found to perform this integration so an average concentration is calculated from equations [52] or [53] using an average distance between the depth at the start of runoff and the final projected depth. Examination of the behavior of these equations indicates that there will be an underestimation of the mean concentration when the runoff and infiltration remain constant. However, the infiltration is usually higher at the beginning of the storm, carrying a larger fraction of the high concentration into the soil, which reduces the underestimation. The total amount of chemical lost in runoff is calculated as the product of the mean concentration during the runoff and the amount of runoff.

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Interrill erosion, step 5.—Sediment from erosion has higher concentrations of clay, organic matter, nitrogen, and phosphorus than the original soil. The enrichment coefficient is the ratio of the concentration in the sediment to the concentration in the original soil. The highest enrichment coefficients tend to occur with the smallest amounts of erosion. Increasing amounts of erosion tend to bring the ratio closer to unity [55]. This suggests that the sediment from rill erosion has the same composition as the soil and that the enrichment is the contribution of interrill erosion which is predominantly silt and clay. Enrichment coefficients of two are quite common for clay, organic matter, etc., from erosion plots.

The erosion model supplies estimates of the clay enrichment coefficients, EC, the pounds of interrill and rill erosion, GI and GR, for each compartment in the watershed, and the clay fraction, CF, and silt fraction, SF, of the surface soil in each zone. The pounds of clay in the interrill erosion, PC, is the total clay in the sediment minus the clay from rill erosion:

$$PC = (CF \cdot EC)(GI + GR) - CF \cdot GR \qquad [55]$$

and the pounds of silt, PS, is the remainder.

There are numerous references, see Bailey and White (1), to the fact that the different size fractions of the soil adsorb chemicals to different degrees. The amount of chemical per unit of soil at the surface comes from the mean concentration during runoff and equation [48]. The fraction of this that is adsorbed to the clay is PF $\cdot$ CF/(PF $\cdot$ CF+SF) where PF is the preference factor of the chemical for the clay relative to the silt when there is none adsorbed on the sand. Therefore, the pounds of chemical per pound of clay, SC, is:

$$SC = \frac{S}{CF} \cdot \frac{PF \cdot CF}{PF \cdot CF + SF} \qquad [56]$$

and the remainder of the chemical is associated with the silt. Similar calculations with an additional preference factor can be used when the chemical is associated with the sand fraction.

The total amount of chemical removed in interrill erosion is the sum of the product of concentration and amount for the clay and silt:

$$AI = SC \cdot PC + SS \cdot PS \qquad [57]$$

Rill erosion, step 6.—The basic logic used for the loss of chemicals in rill erosion is that all the chemical within the rill volume is lost. The area of the rills, EA, as a fraction of the treated area and the average depth of the rills, ED, is provided by the erosion model. Rills are probably wider at the soil surface, but for simplicity a rectangular rill shape is assumed. The method of estimating the width and depth of the rills is crude at this time and doesn't merit a more complex shape consideration. The amount of chemical within the rill volume is the product of the amount of chemical in the compartment, the area of the rills, and the fraction of the vertical distribution intercepted by the rill. This fraction, Y1, is the integral of a unit distribution from the surface to the bottom of the rill:

$$Y1 = \int_{0}^{ED} f(x)dx \qquad [58]$$

When the chemical has been applied to the surface and leached D inches into the soil, then f (X) is a bell-shaped curve about D and the integral is

$$Y1 = 1/2 \cdot \left[ERF\left(\frac{D}{\sqrt{4 \cdot DC \cdot D}} \right) \right.$$

$$\left. \pm ERF\left(\frac{ED-D}{\sqrt{4 \cdot DC \cdot D}} \right) \right] \qquad [59]$$

where the minus sign is used when the argument is negative. A band width of two standard deviations, $2 \cdot \sqrt{4 \cdot DC \cdot D}$, is used to determine how much of the chemical distribution the rill depth intercepts. When the chemical is applied by mixing AP inches into the soil and then leached D inches, a plug with sharp boundaries, f(x) = constant, between D and D + AP is assumed. This creates three limits:

a. When ED is less than D then

$$Y1 = 0 \qquad [60]$$

b. When ED is greater than D but less than D + AP then

$$Y1 = ED/(D + AP) \qquad [61]$$

c. When ED is greater than D + AP then

$$Y1 = 1 \qquad [62]$$

Cultivation that reaches the chemical is assumed to create a plug distribution and destroy the previous rills. Without cultivation the rill erosion is assumed to occur

in the old rills, and the effect of the combined rill depth must be used in setting the integral Y1. Summarizing, the amount of chemical lost in rill erosion is

$$AR = A \cdot EA \cdot Y1 \qquad [63]$$

Transport to the channel, step 7.—Runoff water and sediment from one zone can cascade over other zones. The transformation of watershed into a series of tubes was used to describe this feature. The amounts of runoff water, sediments, and any chemical associated with them are accumulated for all the compartments in a tube. Currently no allowance is made for loss of the chemical over untreated ground by infiltration or adsorption on the soil surface. One estimate of the amount lost by infiltration is the product of the infiltration during runoff and the concentration equilibrated with the water and sediment of runoff in that compartment. In most cases these effects are considered to be small. Since the soils could be different in their adsorption and preference characteristics as well as texture, the amounts of clay and silt are calculated. The absorption and preference factors are weighted for the amount of sediment from each zone, and the chemical distribution between the sediment and water is calculated for the outflow of each compartment.

Deposition, step 8.—In some compartments the flow of runoff water will be insufficient to maintain all the sediment in suspension and the excess sediment will be deposited. The hydrodynamic characteristics of the sediment cause the larger, heavier particles to settle out first. In most cases these heavier particles are sand grains containing a negligible amount of chemical. It is recognized that sometimes water-stable aggregates and organic-coated grains may cause a significant fraction of the chemical load to be deposited with the sand fraction. The chemical is distributed according to the weighted adsorption coefficient between water and sediment before the deposition. The amount of deposition is satisfied by depositing the sand, silt, and clay in that order. The weighted preference factor is used to calculate the deposition of the chemical with the different size fractions.

Lateral outflow, step 9.—The hydrology model provides estimates of the vertical and lateral flow rates for each layer in each zone. The compartments at the end of tubes are next to the channel, and chemicals in these compartments can be carried into the channel by lateral flow. Water is also contributed to the outflow of each tube.

The amount of lateral waterflow is the ratio of the lateral flow rate to the total flow rate times the amount

of drainage. The amount of drainage from each layer is the amount of infiltration to each layer minus the amount required to reach field capacity. Since the chemical could be distributed between two layers, the fraction in each layer must be calculated. For a bell-shaped distribution the fraction above the boundary is given by equation [58] where ED is replaced by the distance to the boundary. The fraction for a plug distribution is the difference between the boundary and the top of the plug divided by the thickness of the plug. The chemical outflow from each layer is then the amount of chemical in solution times the outflow divided by the amount of water in the soil.

Mixing for watershed outflow, step 10.—The outflow from a watershed is not usually a well-mixed system. Pairs of samples taken at the same time can differ in concentration from 9 to 33 percent (11). Some of this variability can be attributed to the cascading effect symbolized by the tube transformation in this model. Thus one estimate of the peak solution concentration in the outflow is from the average solution concentrations in each tube outflow. The combination of all the tubes gives the watershed outflow with a mean solution concentration calculated by distributing all the chemical between all the sediment and all the water.

Location of the remaining chemical, step 11.—The presence of a lateral component of waterflow results in a diagonal movement of the chemical through the soil profile. The total distance moved has been calculated from the infiltration. The vertical and horizontal components are calculated from each increment of movement using the ratio of lateral to vertical flow rates weighted for the fraction of the chemical in each layer. The peak solution concentration is calculated from equations [52] or [54]. The deposited chemical is added to the chemical already in that compartment or creates a new treated area if there is no previous chemical. A plug distribution is assumed with a thickness of 1 inch plus the depth of the chemical layer already there.

The logic for cultivation effects.—If the depth of cultivation is deeper than half the chemical, it is assumed that a plug distribution is created from the surface to the depth of the cultivation.

Iteration.—The preceding calculations are performed for each compartment in the watershed although some steps can be omitted if no chemical is present. After the calculations are completed for the entire watershed, the results are totaled and the status of the system is printed

out. The program then returns to the beginning for another storm event.

The Nitrate Option

Nitrate is derived in the soil not only by fertilizer application, but also by the mineralization process of micro-organisms. Nitrogen in organic matter is converted to ammonium, then to nitrite, and finally nitrate. Nitrite seldom occurs in significant concentrations and while ammonium occurs at significant concentrations more frequently, it is moderately adsorbed to the soil. Thus the nitrogen problem is usually restricted to nitrate which is nonadsorbed and leached easily. Plant uptake, denitrification, and immobilization are other mechanisms for nitrate removal.

Since erosion can remove adsorbed organic forms of nitrogen and ammonium, but does not significantly affect the nitrate movement, the erosion model was bypassed and the storm file, from the hydrology model normally used by the erosion model, is used directly. The elimination of the erosion model also eliminates the need to consider compartments within the hydrologic zones. Normal mineralization means that the nitrate movement in all zones has to be calculated, whether the zones received fertilizer or not. The starting date for the simulation is the date of the first application of fertilizer. The model provides the option for a split application of fertilizer to be applied on a second date. Table 7 presents an outline of steps used in calculating nitrate movement.

Mineralization, step 1.—Organic nitrogen is mineralized to nitrate according to a first order rate equation (45). The pounds per acre of nitrate, AN, from mineralization during a period of TI days is:

$$AN = PN[1.-EXP(RK \cdot TI)] \qquad [64]$$

where PN is the pounds/acre of potentially mineralizable nitrogen in the top layer of soil, and RK in reciprocal days is the mineralization rate coefficient. The rate coefficient is sensitive to temperatures (46) and moisture (47). The Arrhenius equation relating the rate coefficient to TM, the average absolute temperature (273 + degrees Celcius) during the period, is

$$\ln(RK) = 15.807 - 6350./TM \qquad [65]$$

The optimum moisture for mineralization appears to be near field capacity, and the rate coefficient decreases linearly as the moisture content decreases:

$$WC = SW/FC \qquad [66]$$

Table 7.—Outline of steps for tracing nitrate movement

1. Mineralization, temperature, and moisture corrections.
2. Plant uptake.
3. Fertilizer and cultivation.
4. Vertical movement and lateral outflow.
5. Iteration and band completion.

where WC is the correction for the soil moisture content, SW, averaged over the period of mineralization. When the moisture content is above field capacity, the conversion of ammonium to nitrate is inhibited but the conversion of organic nitrogen to ammonium is not. Short periods of ponding are incorporated in the model through the second infiltration stage. Any ammonium buildup is dissipated quickly to nitrate when aerobic conditions return.

Ponding does accentuate denitrification which is not accounted for in this model. Considerable study was given to this process before it was decided to neglect the process in this version. The presence of a carbon source is necessary for the conversion of nitrate to gases, and this would require additional modelling of soluble carbon compounds. The same problem was faced and the same decision was reached for the process of immobilization, the conversion of nitrate into organic nitrogen compounds. These are areas for future research.

Plant uptake, step 2.—The uptake of nitrate by the crop is the mechanism of greatest nitrate loss during the time when plants are actively growing. Unpublished work indicates that when the accumulated mineralization plus fertilizer does not greatly exceed the amount of nitrogen for optimum plant growth (44) only a small amount of nitrate remains in the root zone at plant maturity.

Laboratory studies (51) show that nitrogen uptake increases with the increasing concentration of nitrate in solution. Mass flow is the predominant mechanism for moving nitrate through the soil to the plant root (2). Thus nitrogen uptake should be closely connected to evapotranspiration. Evapotranspiration is also related to the amount of adsorbing root surface and reflects the growth rate of the plant. There is little growth, ET or nitrate uptake under cold or drought conditions (52). Based on these considerations the nitrate taken up by the plant, UP pounds/acre, during the period between storms is:

$$UP = AU \cdot ET/(SW \cdot WD) \qquad [67]$$

where AU is the pounds of nitrate per acre available for uptake, the initial content plus half the mineralized amount; ET is the inches of evapotranspiration from each layer weighted for the distribution of the nitrate

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within layers and the product of SW and WD gives the inches of water in the soil.

Fertilization and cultivation, step 3.—Fertilizer added before a storm is not considered available for uptake because uptake from split applications of nitrogen is small if there isn't adequate moisture. The applied fertilizer is available for leaching during the storm and for uptake after the storm. Cultivation is not considered directly in the nitrate model, but its effects on water movement are accounted for in the hydrology model.

Movement, step 4.—The same logic is used for the leaching of nitrate as is used in the general chemical model. Infiltration causes vertical movement and lateral outflow which is added to the surface runoff. There is no nitrate carried in the surface runoff except as contributed by return flow, and no loss by erosion or deposition is calculated. The model could be modified to handle a surface application of nitrogen fertilizer using a

dissolution rate rather than assuming complete dissolution in the initial infiltration.

Iteration and band completion, step 5.—The preceding calculations are repeated for each zone to provide the watershed output. All the calculations are repeated for each storm event causing the band of nitrate to move downward. Since mineralization is assumed to occur in the top layer, the mineralization subsequent to each storm in effect creates a layer that is thicker by the amount of movement. When the mineralization rate is slow enough, its contribution to the band of nitrate can be bypassed and this defines the location of the top of the band. This decision is made when the average temperature is 5° C or less. The temperature relation indicates that the mineralization rate at 5° C is about 10 percent of optimum.

Any infiltration during this cool weather (fall, winter and spring), causes the band to move further. No explicit provisions have been made for frozen conditions. These are presumably handled by the hydrology model.

TESTS FOR VALIDATION

Carbofuran Experiment at Coshocton, Ohio

Complete data sets of chemical, erosional, and hydrological information are very scarce. The only complete set we have been able to compile is for a 2-year experiment with the pesticide carbofuran on watershed No. 113 at the North Appalachian Experimental Watershed, Coshocton, Ohio. The data set was developed from the manuscript reporting the results (6) and supplemented with information from the authors and the staff at the watershed.

Input to the Hydrological Submodel

Tables 8 and 9 give the input format for the parameters and data. The 1.5-acre watershed was divided into three equal zones as shown in figure 17. The upper zone had an average length of 80 ft and slope of 3 percent. The middle zone was 110 ft with a 10-percent slope and the lower zone was 190 ft with 20-percent slope. While there is subsurface movement of water in this watershed, none of it comes to the surface above the measuring weir. Corn was grown on the whole watershed the 2 years of the experiment, 1971 and 1972. To initialize the hydrologic conditions, the hydrology submodel was operated for the 2 years preceding the experiment when the watershed was in meadow. Temperature and pan evaporation were entered as weekly

averages of the daily values, mean degrees Fahrenheit and inches.

The rainfall input was breakpoint values. Each observation contained the date, military time, and the inches of precipitation since the previous reading. The time increment between observations did not exceed 2 months when there was no rainfall and 30 minutes during storm.

Input to the Erosion Submodel

The information about each compartment needed by the erosion submodel is given in table 10.

In watershed 113 all the overland flow cascades to the next zone so there is only one stream tube or path. The hydrologic variables required are the runoff volume, peak runoff rate, and the rainfall intensity for each zone in each storm. The slope length and steepness are the same as used in the hydrology. In addition, the soil texture, 15 percent clay and 60 percent silt, the erodibility factor, 0.48, the crop factor for corn changing from 0.29 to 0.43 with season, and the management factor of 0.5, 0.6, and 0.9 for these zones are used.

Input to the Chemical Submodel

Table 11 lists the information required by the chemical submodel for each compartment. Only one layer per compartment is necessary because of the limited leaching.

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Table 8. USDA HYDROGRAPH LABORATORY 1973 MODEL OF WATERSHED HYDROLOGY – PARAMETERS

Left justify. Use decimal in all fields except those of STORMDATES and TILLAGE.

SECTION (reference)	MAX#/CARD	1 thru 8	9 thru 16	17 thru 24	25 thru 32	33 thru 40	41 thru 48	49 thru 56	57 thru 64	65 thru 72	73 thru 80
COLUMNS											
IDENTITY	2	WATERSHED IDENTITY, RAINGAGE, PERIOD OF RECORD, ETC.									
STORM DATES	5	MMDDYY	(10 dates per card. Data must end in 8 col. blank field unless there are 50. Insert blank if none.								
WATERSHED (figs. 1, 6, 7, 8)	1	W/S ACRES	NUMBER OF ZONES	NUMBER OF ROUTING COEFFICIENTS — TOTAL	ABOVE WEIR	NUMBER OF CROPS	DEEP GROUND-WATER RE-CHARGE. IN/HR.	LAND USE CHANGES- YES OR NO?	TILLAGE CHANGES- YES OR NO?		
ZONE (see fig. 1, fig. cit. 18, table 2)	4	Z NUMBER	% W/S	LENGTH FT	% SLOPE	FC IN/HR	TOP SOIL IN	TOTAL SOIL IN. *Use 1 card for each zone. Delete rest			
(rows)		1.									
		2.									
		3.									
		4.									
SOILS (table 3)	4	Z NUMBER	% G1	% AWC1	% ASM1	% CRACKING1	% G2	% AWC2	% ASM2	% CRACKING2	
(rows)		1.									
		2.									
		3.									
		4.									
CHANNEL	1	ΔT HRS	Mc HRS	INITIAL IN/HR.	INIT. SNOW						
		q1 IN/HR.	m1	q2	m2	q3	m3	q4	m4	Delete card if all zeros.	
SUBSURFACE (fig. 1)	1	% SUB FLOW DIVERTED TO CHANNEL	% Z1 CASCADING Z2	REMAINDER TO "CHANNEL" OR "ALLUVIUM"?	% Z2 TO Z3	REMAINDER	% Z3 TO Z4	Delete if only one zone.			
CASCADING	1										
LAND USE (table 4B)		CROP 1	CROP 2	CROP 3	CROP 4	CROP 5	CROP 6	CROP 7	CROP 8	CROP 9	CROP NAMES
											A VALUE
(table 2)											Vd IN.
(see table 4A)											ET/EP
											ROOT DEPTH IN
											TU
											TL
COLUMN		1 – 8	9 – 16	17 – 24	25 – 32	33 – 40	41 – 48	49 – 56	57 – 64	65 – 72	73 – 80

NOTES:

Table 9. USDA HYDROGRAPH LABORATORY 1973 MODEL OF WATERSHED HYDROLOGY – DATA

SECTION	COLUMNS 1		49	57	65	73	80
TEMPERATURE	IDENTIFICATION AND YEAR		TEMP WEEK₁	WEEK₂	WEEK₃	WEEK₄	

52 values (rows 1–12)

COLUMNS: 1-8 | 9 | 11-13 | 14-19 | 21-23 | 24-29 | 31-33 | 34-39 | 41-43 | 44-49 | 51-53 | 54-59 | 61-63 | 64-69 | 71-73 | 74-79

COLUMNS	1-8	9	11-13	14-19	21-23	24-29	31-33	34-39	41-43	44-49	51-53	54-59	61-63	64-69	71-73	74-79
TILLAGE	CROP NAME	GZ	TIL	MMDDYY	TIL	MMDDYY	TIL	MMDDYY	TIL	MMDDYY	TIL	MMDDYY	TIL	MMDDYY	TIL	MMDDYY
			B		B		B		B		B		B		B	
			L		L		L		L		L		L		L	
			A		A		A		A		A		A		A	
			N		N		N		N		N		N		N	
			K		K		K		K		K		K		K	

COLUMNS	9									
LAND USE %	NUMBER	% CROP1	% CROP2	% CROP3	% CROP4	% CROP5	% CROP6	% CROP7	% CROP8	% CROP9

(rows 1. 2. 3. 4.)

BLANK CARD

	IDENTIFICATION AND YEAR		49	57	65	73	80
PAN EVAPORATION	IDENTIFICATION AND YEAR		EP IN/DA WEEK₁	WEEK₂	WEEK₃	WEEK₄	

52 values (rows 1–13)

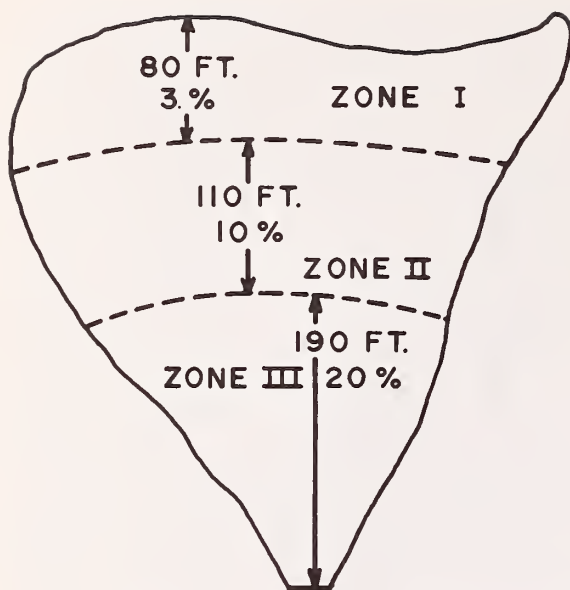| COLUMNS	1-8	9-16	17-24	25-32	33-40	41-48	49-56	57-64	65-72	73-80

Figure 17.—Watershed 113 divided into three hydrological zones.

From the hydrology submodel the values of the initial soil moisture, infiltration, runoff, and subsurface movement are needed. The erosion submodel supplies values of interrill and rill erosion, area and depth of rills, deposition, and composition of the sediment. The chemical characteristics used are given in table 12. In 1971 the carbofuran was broadcast on the soil surface and disced 3 inches into the soil before the corn was planted. In 1972 the carbofuran was banded 2 inches deep with the corn seed. The adsorption coefficient was calculated from the concentration on the sediment and in the solution while the breakdown coefficient was reported in the manuscript. The banding method increased the adsorption coefficient threefold and decreased the breakdown coefficient twofold. The dispersion distribution coefficient and the preference factor were chosen arbitrarily as "reasonable" values after consulting the literature.

Results

The predicted values of five variables are compared with measured values for five storms in table 13. In 1971 rain started in the evening following application and continued the next morning to give the only major storm that season. Five·other storms with less than 0.05 in. of runoff were measured but not predicted by the hydrology model.

In 1972, 26 days passed from the time of application until the first storm runoff was measured. Rain totaling

0.64 in. fell during this period and was treated as initial infiltration. During the 25 days between the second and third storms, 2.49 in. of rain fell and was treated as part of the initial infiltration. Eight other storms with less than 0.08 in. runoff were measured, but not predicted by the hydrology submodel before the November 7, 1972, storm.

Table 10.—Erosion submodel input data for each compartment

Constant watershed characteristics

    1. Soil erodibility factor
    2. Slope steepness, percent
    3. Length of overland flow, ft
    4. Width of compartment, ft
    5. Texture

Variable watershed characteristics

    6. Crop factor
    7. Management factor

Storm characteristics

    8. Rainfall factor from storm intensity
    9. Volume of runoff, in
  10. Peak rate of runoff, in/hr

Table 11.—Information required for the chemical submodel

A. Chemical

    1. Date of application
    2. Application rate, lbs/a
    3. Depth of mixing, in
    4. Adsorption coefficient, ratio of concentrations
    5. Breakdown coefficient, day^{-1}
    6. Relative preference for size fractions

B. Physical

    7. Dispersion distribution factor, in
    8. Field capacity, %
    9. Porosity, %
  10. Texture of soil

C. Hydrological

  11. Date of storm
  12. Infiltration before runoff, in
  13. Infiltration during runoff, in
  14. Runoff, in
  15. Ratio of lateral to vertical flow
  16. Soil moisture at start of storm

D. Erosional

  17. Interrill erosion, tons
  18. Rill erosion, tons
  19. Fraction of area in rills
  20. Depth of rills, in
  21. Deposition, tons
  22. Texture of sediment

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Table 12.—Characteristics of carbofuran experiments on Coshocton Watershed 113

Date of application	May 5, 1971	May 18, 1972
Amount applied, lb/a	4.83	2.77
Application method	Broadcast	Banded
Depth of mixing, in	3	2
Adsorption coefficient	1.4	4.1
Breakdown coefficient, day^{-1}	0.015	0.0074
Dispersion distribution coefficient, in	.5	.5
Preference factor	10	10

The predicted chemical loss and concentration are high. Only preliminary efforts have been made so far to evaluate the cause of the discrepancies from the three models. Additional results from other chemicals, storms, and watersheds are needed before a thorough evaluation can be made.

A more detailed analysis of the 1971 storm is given in table 14. About 64 percent of the chemical loss is removed by runoff water in this storm. A similar analysis of the 72 storms shows a decrease in the fraction of the chemical loss from runoff water as the chemical is

Table 13.—Measured and predicted water, sediment, and carbofuran losses from Coshocton Watershed 113 for 5 storms

Item	Storm date				
	5-6-71	6-13-72	6-15-72	7-10-72	11-7-72
Runoff, in					
Meas.	0.21	0.24	0.41	0.20	0.22
Pred.	.21	.46	.27	.001	.15
Peak flow, cfs					
Meas.	.28	.85	3.54	4.24	- - -
Pred.	.23	1.15	.83	.01	.27
Erosion, tons/a					
Meas.	1.73	2.12	4.49	.69	.38
Pred.	4.27	9.53	4.80	.80	3.60
Carbofuran, lbs					
Meas.	.036	.021	.046	.004	.001
Pred.	.071	.15	.104	.04	.013
Concentration, ppm					
Meas.	.47	.19	.22	.05	.02
Pred.	.78	.56	.70	4.24	.14

Table 14.—The movement of water, sediment, and carbofuran in each compartment for the 1971 storm

Item	Compartment			Total watershed
	1	2	3	
Initial infiltration, in	1.64	1.55	1.99	- - -
Remaining infiltration, in	.99	.84	1.38	- - -
Runoff water, in	.38	.62	-.36	- - -
Runoff chemical, lb	.0265	.0454	-.0268	.0451
Interrill soil, tons	.1	.1	.5	- - -
Interrill chemical, lb	.0002	.0002	.0003	.0007
Rill soil, tons	0	1.1	4.9	- - -
Rill chemical, lb	0	.0046	.02	.0246
Leaching depth, in	.85	.87	1.03	- - -
Remaining chemical, lb/a	4.7	4.6	4.8	- - -

leached deeper into the soil. The negative values for runoff water and chemical in compartment three occurred because the infiltration in this compartment exceeded the rainfall and part of the cascading water from the second compartment was used.

Erosion Studies at Treynor, Iowa

Since additional complete chemical, erosional, and hydrological data sets are not presently available, other data sets have been used to evaluate parts of the model. The hydrology submodel has been evaluated with a number of data sets (20) and will not be discussed here. A set of hydrological and erosional data from watershed 2 at Treynor, Iowa, was obtained from the staff of the North Central Watershed Research Center, Columbia, Mo., and used to evaluate the combination of the hydrological and erosional submodels.

Input to the Hydrological Submodel

A map of the 82.8-acre watershed is shown in figure 18. The watershed was divided into three zones: 200 ft; 166 ft; and 133 ft in average overland flow length. It was estimated that twenty percent of the upper zone cascaded to the middle zone while 15 percent of that zone cascaded onto the lower zone. In 1965 corn was grown, and in the 10-day period from June 25 to July 4 six major runoff events occurred. To initialize the hydrological conditions the hydrology submodel was started the previous year when corn was also grown.

Input to the Erosional Submodel

To compute the erosion variables the watershed must be transformed. The transformation creates five stream tubes or paths and seven compartments as shown in figure 19. For this silt loam soil the texture is 15 percent clay and 65 percent silt, the erodibility factor is 0.32, the crop factor for corn is 0.5, and the management factor is 0.8 in the upper zone and 0.7 for the other zones.

Results

Comparisons of the measured and predicted runoff characteristics are given in table 15, for the six storms. In general, the predicted values exceed the measured

values with the greatest error associated with the largest storm. The erosion-deposition characteristics for these six storm events are given in table 16. The only large discrepancy between measured and predicted sediment yield is for the June 29 storm when the hydrologic characteristics were also most in error. The detailed erosion results of each compartment are given in table 17 for the second storm on June 28, 1965. These results illustrate the deposition of sediment in the lower compartment of the D stream tube.

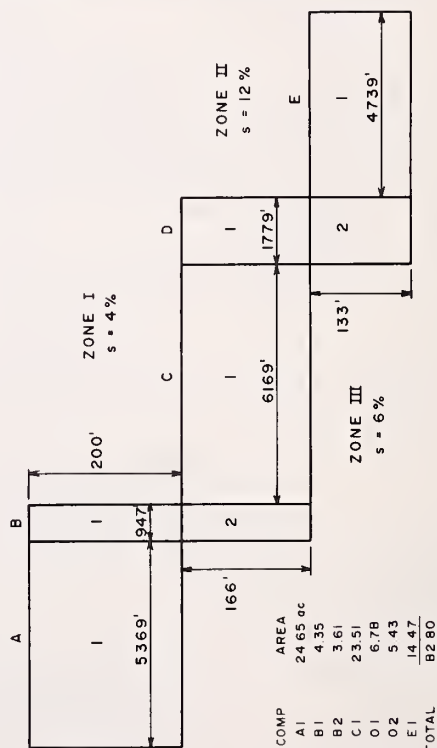Figure 18.—Treynor, Iowa Watershed 2. (82.8 acres)

Figure 19.—Treynor Watershed W-2 transformed.

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Table 15.—Runoff characteristics, Treynor Watershed W-2, 6 storm events—6-27-65 to 7-1-65

| Date | Rainfall | Runoff | | | |
| | | Measured | | Predicted | |
		Volume	Peak	Volume	Peak
	In	*In*	*Cfs*	*In*	*Cfs*
6-27	0.53	0.04	20	0.16	51
6-28	.62	.16	72	.33	132
6-28	1.20	.68	152	.92	204
6-29	2.42	.64	157	1.51	384
7-1	.68	.13	51	.12	39
7-1	.25	.05	21	.02	3

Table 16.—Erosion-deposition characteristics, Treynor Watershed W-2, 6 storm events—6-27-65 to 7-1-65

| Date | Rainfall amount | R | Measured sediment yield | Predicted sediment yield | Erosion | | Deposition |
					Interrill	Rill	
	In		*T/ac*	*T/ac*	*T/ac*	*T/ac*	*T/ac*
6-27	0.53	8.8	0.51	0.98	0.47	0.61	0.09
6-28	.62	8.5	1.84	1.49	.37	1.26	.14
6-28	1.20	31.8	5.36	5.74	1.36	4.90	.52
6-29	2.42	26.4	3.65	8.21	1.01	7.95	.76
7-11	.68	1.6	.58	.33	.07	.30	.03
7-1	.25	.5	.15	.05	.03	.02	.004

Table 17.—Erosion results in each compartment for the 2d storm on June 28, 1965

| Compartment | Interrill | Rill | | | Deposition |
		Amount	Area	Depth	
	Tons	*Tons*	*Percent*	*In*	*Tons*
A1	26.8	38.0	17.7	0.065	0
B1	4.7	6.7	17.7	.065	0
B2	4.1	63.1	24.6	.528	0
C1	39.8	192.9	24.6	.248	0
D1	11.5	55.6	24.6	.248	0
D2	8.6	24.8	20.0	.170	43.5
E1	17.4	24.8	20.0	.064	0

As indicated in the discussion of the submodels, the hydrology submodel has been tested separately on several watersheds and found to produce volumes and peaks corresponding reasonably well to the observed data. The coupling of the hydrology and erosional submodels has been tested twice, once with the five storms on the Coshocton, Ohio watershed and with the six storms on the Treynor, Iowa watershed. The combination of all three submodels has been tested once with the five storms on the Coshocton, Ohio watershed.

An adequate test of this model requires complete sets of chemical, erosional, and hydrologic data for several diverse watersheds. This information is extremely rare because it is only recently that the chemical and physical data have been collected simultaneously. The only published data that approach the necessary requirements are the pesticide work on the Coshocton, Ohio watersheds. Pesticide experiments recently completed on the Riesel, Texas watersheds and currently in progress on the Watkinsville, Georgia watershed may provide some additional tests of the model.

The best tests of any model come from experiments designed for that purpose. Therefore, it is hoped that the chemists and engineers at all of our watershed centers can use this model as a research tool for designing experiments and data collection. The experimental results will provide tests for this version of the model, as well as information for developing better versions.

These experiments will require an unpredictable period of time to complete because of erratic weather. In the meantime, the literature is being examined for data that might serve to test one or two parts of the model. A number of papers have been published on the chemicals in runoff and erosion from simulated rainfall experiments. Some of these may have sufficient data to test the combination of erosion and chemical submodels for a single compartment. A number of leaching experiments might be used to test the leaching aspect of the hydrology and chemical submodel combinations. A few of the numerous nitrogen experiments might have sufficient data to test some aspects of the hydrology and nitrate submodel combination.

It is anticipated that the testing will result in some model concepts being revised or replaced. It is hoped that this model will serve as a stimulus for conducting small experiments to test parts of the model; leaching, dispersion, rill development, etc. The development of the submodels revealed a number of areas where basic research is needed to improve our understanding of important processes. The following few paragraphs highlight some of the most obvious problems.

The path that the water follows through the soil takes on added importance when the chemical aspect is considered. The lateral flow of water below the surface is extremely difficult to monitor and describe. Interflow appears to be the best explanation for the highest chemical concentration in runoff occurring in the second and third storms of some experiments. Snow distribution and melting are poorly understood, particularly in the prediction of runoff and leaching of chemicals. Considerable information and a number of evapotranspiration models have been produced recently, but the root growth and water extraction pattern in the soil is still inadequately understood.

The dynamic or time-dependent aspects of erosion take on added importance when chemical adsorption and distribution is considered. The detachment, transport, and deposition processes depend upon rates as well as volumes of rainfall and runoff. The changing rates of water and soil movement will be reflected in time-dependent chemical movement.

Enrichment ratios indicate the need to characterize the sediment movement beyond amount and time. Even particle size, while very important, is not sufficient to account for the chemical transport properties of aggregates and organic matter. If the concepts of rill and interrill erosion used in this model are shown to be important characteristics of chemical loss by erosion, then a great deal of research will be needed to adequately describe such processes as the formation and configuration of rills.

In the chemical area the washoff of pesticides from vegetation and the leaching of nutrients out of the vegetation are some of the most poorly understood processes. Management practices, such as banding or repeated applications, appear to cause greater effects than expected. The immobilization and denitrification of nitrate continue to be grey areas needing research. The chromatographic theory used in this model is being tested in the laboratory and in small plots and if found to be adequate, considerable work will be needed to measure and predict dispersion distribution coefficients.

The limited target of sloping Corn Belt watersheds must be broadened to include all important agricultural lands. It is believed that the submodels are adequate for most soils. The soils with large cracks are expected to cause the most serious problems. Application of the model to flat or level lands, such as in parts of the Corn

Belt, the delta, and coastal lands, may require alternate submodels. The use of large amounts of chemicals in these areas makes them a most important challenge. Irrigated lands are also flat and receive considerable amounts of chemicals. Only parts of the present hydrology and erosion submodels may be needed to model the flat and irrigated lands. Salinity has not been included because it was felt that there were several modeling attempts already underway and thus more could be accomplished in these other areas.

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